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SOURCES AND DETECTORS OF OPTICAL RADIATION

Saint Petersburg
2017

THE MINISTRY OF EDUCATION AND SCIENCE
OF THE RUSSIAN FEDERATION

ITMO UNIVERSITY

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SOURCES AND DETECTORS OF OPTICAL RADIATION

RECOMMENDED AS A TEXTBOOK
for 12.04.02 "Optical Engineering" Master program, ITMO University

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2017

Valery V. Korotaev, Anton A. Maraev. Sources and detectors of optical radiation. – Saint Petersburg: ITMO University, 2017. – 104 pages

This textbook contains theoretical material for studying of the same-named subject. The order of topics follows the structure of the lectures given at ITMO University at the Department of Optical-Electronic Devices and Systems. Laws of photometry and thermal radiation as well as function and specifications of sources and detectors are considered. The textbook is intended for foreign students majoring in the Master's degree program 12.04.02 — "Optical Engineering".

ITMO UNIVERSITY

ITMO University is the leading Russian university in the field of information and photonic technologies, one of the few Russian universities with the status of the national research university granted in 2009. Since 2013 ITMO University has been a participant of the Russian universities' competitiveness raising program among the world's leading academic centers known as "5 to 100". The objective of ITMO University is the establishment of a world-class research university being entrepreneurial in nature aimed at the internationalization of all fields of activity.

CONTENTS

PREFACE

Optical-electronic devices have a range of advantages over visual inspection, such as:

- information is collected in the entire electromagnetic spectrum, not only in its visible part,
- modern applications require automatic measurements,
- information needs to be stored and processed, etc.

The purpose of this course is to provide advanced knowledge of sources and detectors of optical radiation, their properties, characteristics, and schemes to design various optical-electronic systems.

In this course you will learn how to

- Characterize emitted and incident light in terms of radiometry.
- Describe a thermal radiation source.
- Operate radiation sources of various types.
- Define important detector response characteristics, including responsivity, noise equivalent power, quantum efficiency, etc.
- Define sources of detector noise and methods employed to reduce the effect of these noise sources.
- Describe and explain the operation of common types of photodetectors.
- Draw and explain a typical circuit for a photovoltaic and photoconductive detector.
- Calculate the noise equivalent power of a detector and detectivity of a detector.

The structure of the edition follows the lectures notes on Sources and Detectors of Optical Radiation given by the Optical Electronic Devices and Systems department, ITMO University, and can be used for students' self-study.

The following basic sections of the course are considered: Chapter 1 contains common issues and principles of an optical-electronic device design; bases of photometry and radiometry are given in Chapter 2; Chapter 3 deals with thermal radiation laws; Chapter 4 describes radiation sources; Chapter 5 classifies detectors and relevant conversions of their parameters; Chapter 6 contains information on photon detectors; thermal detectors are discussed in Chapter 7; Chapter 8 deals with imaging sensors.

This textbook is based on foreign and Russian literature on this subject. The texts used in the edition are the property of the corresponding authors. The structure of these lecture notes is based on the subject teaching experience at ITMO University.

The edition is provided with the Annex containing relevant literature for further reading in Russian as well as in English to consider deeply specific questions.

Предисловие

Использование оптико-электронных приборов дает ряд преимуществ над визуальным наблюдением:

- информацию можно получить во всех областях электромагнитного спектра, а не только в его видимой части,
- возможность выполнять автоматические измерения,
- информацию можно хранить и обрабатывать, и др.

Цель данного курса — расширить знания студентов об источниках и приемниках излучения, их свойствах, характеристиках и схемах включения.

В этом курсе вы узнаете, как

- охарактеризовать испускаемое и принимаемое излучение с помощью фотометрических величин,
- описать спектр источника теплового излучения,
- использовать источники излучения различных типов,
- определить важные характеристики реакции приемника на падающее излучение, такие как чувствительность, пороговый поток, квантовую эффективность и т.д.,
- определить источники шума приемника и способы уменьшения их воздействия этих источников,
- описать и объяснить принцип работы основных типов приемников,
- составить и объяснить типовую схему включения приемников на внутреннем фотоэффекте,
- рассчитать пороговый поток и обнаружительную способность приемника.

Настоящее учебное пособие повторяет структуру лекционного курса «Источники и приемники оптического излучения» данной дисциплины, преподаваемой в Университете ИТМО на кафедре оптико-электронных приборов и систем, поэтому пособие может использоваться в качестве основы для самостоятельной подготовки студентов.

В пособии рассмотрены основные разделы курса: в главе 1 представлены общие положения и принципы построения оптико-электронных приборов; в главе 2 приводятся основы фотометрии; в главе 3 приводятся законы теплового излучения; глава 4 посвящена источникам излучения, в главе 5 приводится классификация приемников, основные параметры и характеристики приемников излучения и их пересчет; в главе 6 идет речь о фотоэлектрических приемниках; в главе 7 рассматриваются тепловые приемники; в главе 8 рассмотрены приемники, используемые для получения изображения.

При подготовке пособия были использованы материалы современных зарубежных и российских изданий по данной теме. Отрывки текстов, использованных при составлении пособия, являются собственностью соответствующих авторов. При построении структуры пособия учитывался опыт преподавания этой дисциплины в Университете ИТМО.

Издание снабжено справочным приложением, в котором приводится список актуальной литературы для более глубокого изучения отдельных вопросов.

1. INTRODUCTION TO THE COURSE

All objects in the real world emit radiation, which contains information about shape, color, dimensions, position, energy state of objects. To characterize an object, we must transform radiation: It should be converted into other types of energy we are able to record or process. In an optical-electronic system, the energy of an optical signal is transformed into electrical signal energy.

This electrical signal contains information about the object. The radiating object is characterized with the electrical signal parameters, such as amplitude, frequency, phase, pulse length, etc. These electric parameters can be registered, processed with an appropriate algorithm, transferred, output to an operator, or used for automatic control of the manufacturing process.

1.1 Electromagnetic range

Optical radiation over the range from vacuum ultraviolet to the far-infrared or submillimeter wavelength (25 nm to 1000 μm) is considered. The spectral ranges are presented in Table 1.1 [1]:

Table 1.1 — Ranges of electromagnetic spectrum

Electromagnetic range, μm	Name of the range	Designation
0.025-0.2	vacuum ultraviolet	VUV
0.2-0.38	ultraviolet	UV
0.38-0.78	visible	VIS
0.78-1	near infrared	NIR
1-3	short-wavelength infrared	SWIR
3-5	medium-wavelength infrared	MWIR
5-14	long-wavelength infrared	LWIR
14-30	very long wavelength infrared	VLWIR
30-100	far-infrared	FIR
100-1000	submillimeter	SubMM

Radiation with wavelength more than 1 μm belongs to the radio band and with wavelength less than 1 nm to the short-wave spectrum region. Most optical electronic devices operate in the visible range (0.38–0.78 μm) and the near infrared (0.78–1 μm), as well as in the UV region or the middle and the far infrared, e.g. thermal vision systems. Thus, appropriate sources and receivers are applied for each range.

1.2 Electromagnetic radiation properties

Light can be treated as a particle-like or as a wave. Electromagnetic waves share six properties with all forms of wave motion:

- Polarization
- Superposition
- Reflection
- Refraction
- Diffraction
- Interference

Spatial coherence relates to electromagnetic fields measured at the same instant in different points in space. The maximum distance between these points, when emitted waves can still interfere, defines the size of spatial coherence (field correlation radius). For most light sources spatial coherence is defined by their dimensions.

Temporal coherence is defined by non-monochromacity of the light source. This concept relates to the same point in space, but in different time moments. Maximum time period, when interference can be still observed, is called coherence time; $\tau_{coh} = 1 / \Delta\nu$, where $\Delta\nu$ is the spectral width of radiation.

Coherence length is a way that a light beam travels in coherence time: $l_{coh} = c\tau_{coh} = c / \Delta\nu$. It defines the maximum path difference between two beams.

Continuous laser has the biggest coherence time and length among modern light sources.

Quantitative aspects of radiation are defined with radiometric and photometric quantities which will be further discussed in Chapter 2.

1.3 Sources and detectors in optical electronic devices

Over the last decades optical instruments have enabled a plenty of important applications where the human eye is not used as a receiving part of a system anymore. This has led to introduction of multiple electronic parts, consideration of information treatment methods and visualization means.

A typical scheme of an optical-electronic system is shown in Fig. 1.1. A light source creates an information carrier, a radiation flux. Any object itself can be considered as a flux source. Normally, a light source is provided by an optical system that directs the flux onto the object or into the receiving optical system (if the light source itself is observed). The receiving optical system collects the flux that is radiated by the light source or reflected from the object, and redirects it onto a light detector. The detector converts the optical signal into an electrical one. The circuit is intended for signal amplification, detection of a useful signal out of a mixture of signal, noise and background components, and logical operations with the detected signal. The output unit represents the signal in the appropriate form for the information consumer (an operator or an operating unit of another system). Composition of blocks differs from one system to another. Every single block indicated here can be a complex device, e.g., the source may have its own optical system, a filter, a modulator, etc.

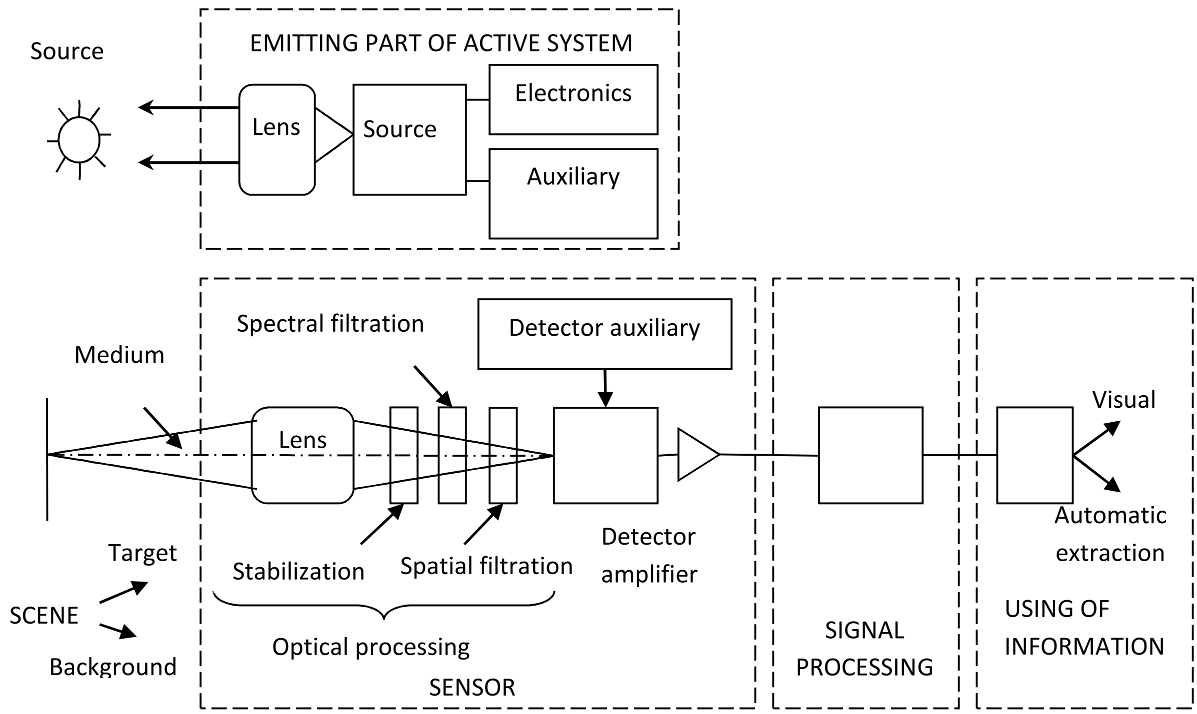


Figure 1.1 – A common layout of an optical-electronic device [2]

In general, the entire system design provides the following: emission of a light signal, its transmission, receiving and proper use of the information obtained. To match components' characteristics while system designing, among other things one should define spatial, spectral and temporal properties of a source, characteristics of the medium or the surface contacted by light, and their effect on the detected light signal. Optical system parameters (field, aperture, resolution quality etc.) should be defined in relation to the detector properties.

1.4 Classification of optical-electronic devices

Optical devices are usually divided into two groups:

- optical devices, where information is perceived only by the human eye,
- devices, where radiation captured by the system is submitted to be transformed into electronic signal, either current or voltage, and then analyzed, processed, stored, accumulated, etc.

Only the devices of the second group will be considered further.

According to the classification given in [3], based on function, optical-electronic systems can be divided into those that transfer, receive and store information, and those that transfer, receive, and transform energy (for instance, solar power-cells) (Fig. 1.2). They can also be classified by the spectral band they use: UV, visual, NIR, MIR, and FIR. Based on information handling they can be classified into non-automatic, which only provide an operator with information, raw or processed, and automatic, which can operate without a human. Optical-electronic devices can also be divided by the purpose they are used for, e.g. angle and distance measurements, television systems, pyrometers and radiometers.

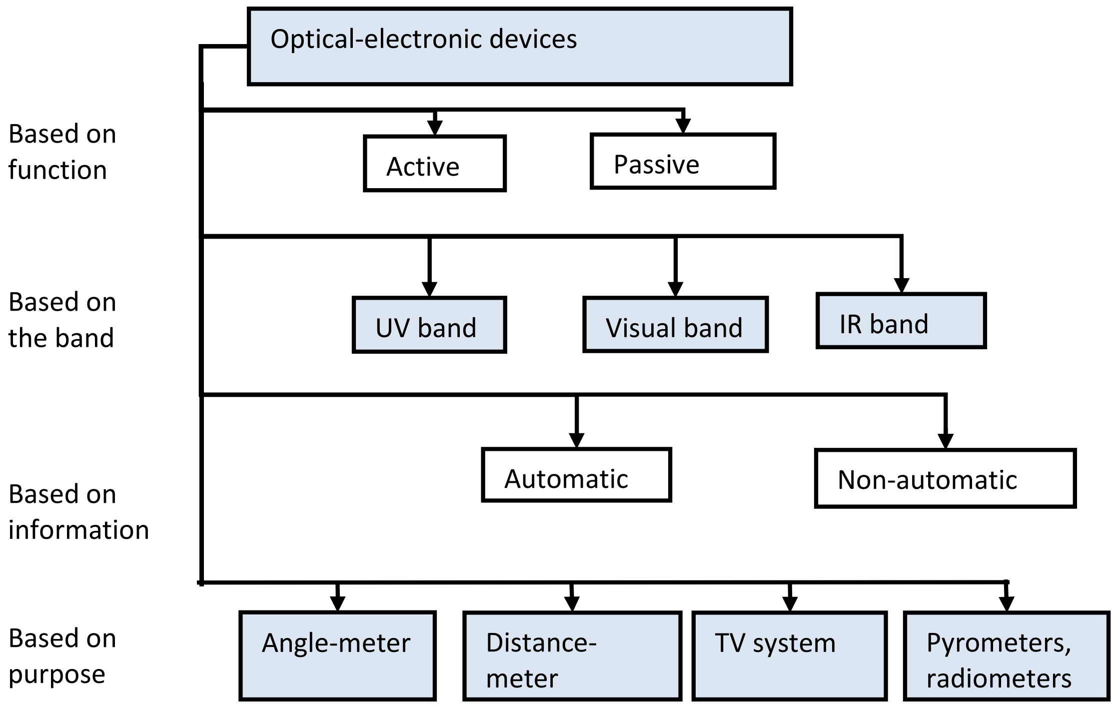


Figure 1.2 – Classification of optical-electronic systems

2. RADIOMETRY AND PHOTOMETRY

Radiometry is the measurement of energy content of electromagnetic radiation fields and the way this energy is transferred from a source, through a medium to a detector. The results of radiometric measurement are usually obtained in units of power, i.e., in watts. However, the result may also be expressed as photon flux (photons per second) or in units of energy (joules) or dose (photons). The radiant power is assumed to be transferred through a lossless medium.

In traditional radiometry, propagation of the radiation field is described using the laws of geometrical optics. Thus, the radiant energy is assumed to be transported along the direction of a ray, and interference or diffraction effects can be ignored. In those situations, where interference or diffraction effects are significant, the flow of energy will be directed differently than geometrical rays. In such cases, the effect of interference or diffraction are often treated as a correction to the result obtained using geometrical optics. This approach is equivalent to the idea that the energy flow travels via an incoherent radiation field. This assumption is widely applicable, since most radiation sources are incoherent to a large degree.

Radiometry is commonly divided according to the regions of the spectrum in which different measurement techniques are used. Thus, vacuum ultraviolet radiometry, intermediate-infrared radiometry, far-infrared radiometry, and microwave radiometry are considered to be separate fields, and are distinguished from radiometry in the visible and near-visible optical spectral region.

It should be noted that there is considerable confusion regarding the nomenclatures of various radiometries. The terminology for radiometry, is dictated not only by its historical origin, but also by the related fields of study. Presently, the recommended practice is to limit the term *photometry* to the measurement of the ability of electromagnetic radiation to produce visual sensation in physically realizable manner, that is, via a defined simulation of human vision [4, 5]. The term radiometry, on the other hand, describes the measurement of radiant energy independent of its effect on a particular detector [1].

There are different types of photometric quantities that are used in the corresponding field. Radiometry deals with radiant quantities, measured in units of energy and denoted with the subscript *e* (example: Φ_e). Units used in photometry are marked with the subscript *v* (example: Φ_v). If the quantity of radiation is expressed in photons, the unit is denoted with the subscript *p* (example: Φ_p).

2.1 Radiometric quantities and basic concepts

Radiometric measurements are traditionally measurements of thermal power (for a steadily emitting source) or energy (for a flashing or single-pulse source).However, due to the quantum nature of most photophysical, photochemical, and photobiological effects, in many applications it is not the measurement of thermal power in the radiation beam, but measurement of the number of photons that would provide the most physically meaningful result [1].

Radiant Energy. Radiant energy is the energy emitted, transferred, or received in the form of electromagnetic radiation.

Symbol: Q Unit: joule (J)

Radiant Power. Radiant power or radiant flux is the power (energy per unit time t) emitted, transferred, or received in the form of electromagnetic radiation.

Symbol: Φ (P) Unit: watt (W)

$$\Phi = \frac{dQ}{dt} \tag{2.1}$$

Irradiance. Irradiance is the ratio of the radiant power incident on an infinitesimal element of a surface to the area of that element, dA_d.

Symbol: E Unit: watt/meter^2(W m^{-2})

$$E = \frac{d\Phi}{dA_d} \tag{2.2}$$

Exitance (also maybe referred to as **Radiant emittance**).

NB: The accepted convention makes a distinction between irradiance, surface density of the radiation incident on a radiation detector (denoted by the subscript d), and the exitance, the surface density of radiation leaving the surface of a radiation source (denoted by the subscript s).

Exitance is the ratio of the radiant power leaving an infinitesimal element of a source to the area of that element dA_s.

Symbol: M Unit: watt/meter^2 (W m^{-2})

$$M = \frac{d\Phi}{dA_s} \tag{2.3}$$

Intensity. Radiant intensity (often simply "intensity") is the ratio of the radiant power leaving a source to an element of solid angle $d\Omega$ propagated in the given direction.

Symbol: I Unit: watt/steradian (W sr^{-1})

$$I = \frac{d\Phi}{d\Omega} \tag{2.4}$$

It should be noted, that in the field of physical optics the word *intensity* refers to the magnitude of the Poynting vector, and thus more closely corresponds to irradiance in radiometric nomenclature.

Solid Angle. The solid angle is the ratio of a portion of the area on the sphere surface to the square of radius r of the sphere. This is illustrated in Fig. 2.1.

Symbol: Ω Unit: steradian (sr)

$$d\Omega = \frac{dA}{dr^2} \tag{2.5}$$

It follows from the definition that the solid angle subtended by a cone of half angle φ, the apex of which is at the center of the sphere, is given by

$$\Omega = 2\pi(1 - \cos\phi) = 4\pi \sin^2\frac{\phi}{2} \tag{2.6}$$

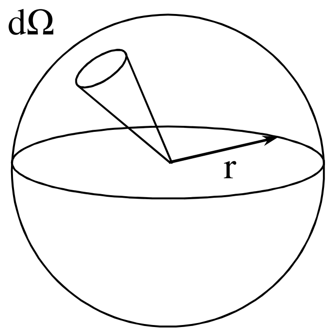


Figure 2.1 –The solid angle at the center of the sphere is the surface area enclosed in the base of the cone divided by the square of the sphere radius

Etendue. Etendue describes the integral of the area and the angular extents over which the radiation transfer problem is defined. Etendue is used to determine the trade-off between the required area and angular extents in non-imaging optic designs.

Definition of étendue is

$$G = n^2 \iint \cos(\theta)\, dA d\Omega, \tag{2.7}$$

Where n is the index of refraction and θ is the angle between the normal to the differential area dA and the centroid of the differential solid angle $d\Omega$ (Fig. 2.2). Thus,

$$d^2G = n^2 \cos\theta dA d\Omega. \tag{2.8}$$

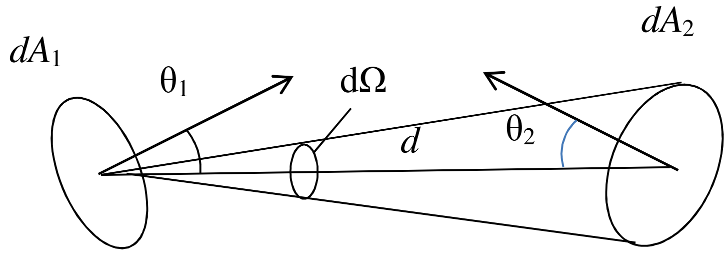


Figure 2.2 –Parameters to characterize the geometrical étendue

As the light propagates through a lossless system or medium, the étendue remains constant.

NB: A lossless optical system cannot reduce geometrical étendue of a pencil of rays, which is a fundamental principle of radiometry Only losing a portion of flux an optical system can reduce geometrical étendue.

Radiance. Radiance is the ratio differential flux $d\Phi$ to the differential étendue, or, in other words, it is the ratio of the radiant power at an angle θ_s to the normal of the surface element, to the infinitesimal elements of both projected area and solid angle (Fig. 2.3). Radiance can be defined either at a point on the surface of either a source or a detector, or at any point on the path of the radiation ray.

Symbol: L *Unit:* watt/steradian meter^2 (W sr^{-1}m^{-2})

$$L = \frac{d\Phi}{d^2G} = \frac{d\Phi}{\cos\theta_s dA_s d\Omega}. \tag{2.9}$$

Radiance is of importance in radiometry because it is the propagation of the radiation that is conserved in a lossless optical system (according to Radiance Conservation Theorem, Homogeneous Medium). Radiance used to be referred to as brightness or specific intensity, but this terminology is no longer recommended.

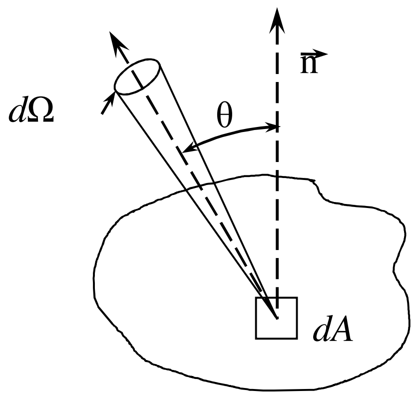


Figure 2.3 – The radiant flux emitted by the infinitesimal area *dA* within the solid angle $d\Omega$, the direction of the flux having the angle θ to the normal to the surface element

From the definition of radiance, it follows that

$$I_e = \int_A L_e \cdot \cos\theta dA \tag{2.10}$$

$$M_e = \int_{2\pi} L_e \cdot \cos\theta d\Omega \tag{2.11}$$

Radiant exposure. Radiant exposure is used for characterizing of radiant energy effect on a detector in time and denoted as time integral of irradiance *E* and time.

Symbol: H *Unit:* watt second/meter^2 (W s m^{-2})

$$H = \int_0^t E(t)\,dt \tag{2.12}$$

There are some other units derived from the considered herein (see [1, 6]) that may be used for a specific application in radiometric measurements.

2.2 Spectral Distribution of Radiometric Quantities

All quantities considered above are integrated by the whole spectrum. To characterize distribution of a quantity by the spectrum, we need to define how to characterize the quantity for a particular wavelength and spectral interval.

For polychromatic radiation, spectral density of a spectral quantity is denoted as either the quantity per wavelength interval or the quantity per frequency interval. The general designation is shown below:

Symbol: X_λ *Unit:* Unit μm^{-1};

or

Symbol: X_f *Unit:* Unit Hz^{-1};

and the quantity is defined by the expression

$$X_\lambda = \frac{dX}{d\lambda} \text{ or } X_f = \frac{dX}{df}. \tag{2.13}$$

It follows that $X_\lambda\, d\lambda$ is the radiant power in the wavelength interval λ to $\lambda + d\lambda$, and $X_f\, df$ is the radiant power in the frequency interval f to $f + df$.

Total radiant power over the entire spectrum is therefore (Fig. 2.4)

$$X = \int_0^\infty X_\lambda d\lambda \text{ or } X = \int_0^\infty X_f df. \tag{2.14}$$

The X can be replaced by any quantity previously considered in Section2.1.

Dependence of spectral density of a quantity on wavelength λ or frequency f is called spectral distribution of the quantity $X_\lambda(\lambda)$.

Sometimes it is more convenient to characterize spectral density distribution of a quantity in relative units. Any relative unit may be obtained as (Fig. 2.4)

$$X_{rel\lambda} = \frac{X_\lambda(\lambda)}{X_{\lambda \max}}, \tag{2.15}$$

where $X_{\lambda max}$ is the maximum value of spectral density of a quantity. A quantity, in relative units, i.e. flux, may be written with a small letter of the corresponding quantity or adding the subscript *rel.*: either φ_λ or Φ_{rel}.

In terms of relative units, the integral quantity (2.14) may be presented as

$$X = X_{\lambda \max} \int_0^\infty X_{rel\lambda} d\lambda. \tag{2.16}$$

In some practical cases reduced photometric quantities (denoted as X_r) are used. They allow to estimate the effect made by a light source on a specific detector. Reduced and radiometric units are related by the following equation:

$$X_r = k \cdot \int_0^\infty X_\lambda \cdot S'(\lambda)\, d\lambda, \tag{2.17}$$

where k is a transformation ratio between radiometric and reduced quantities, $S'(\lambda)$ is relative spectral response of a detector (it defines the level of response to a specific wavelength).

However, radiometric quantities (denoted as X_e and measured in units of power or energy) are used more frequently, as they characterize optical radiation without relation to a detector.

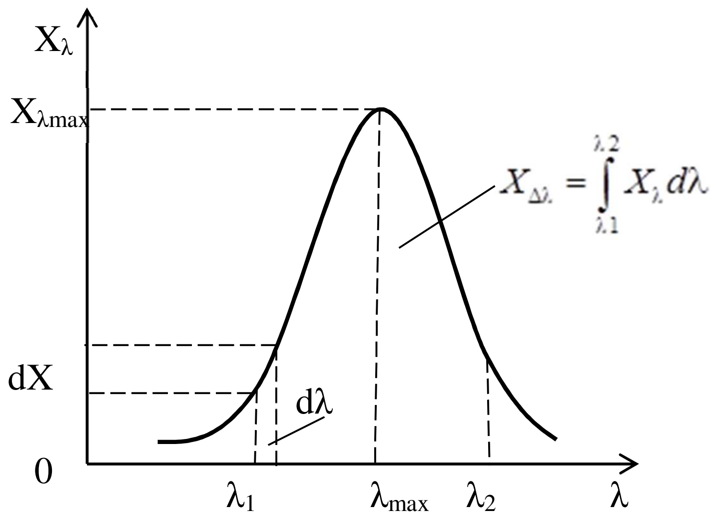


Figure 2.4 – Spectral density distribution of a photometric quantity $X_\lambda(\lambda)$

2.3 Photometric quantities

Photometry is the measurement of radiation that characterizes its effectiveness in stimulating a normal human visual system. Since visual sensation is subjective experience, it is not directly quantifiable in absolute physical units.

Photometry is restricted to the measurement of the visual sensation magnitude regardless of color, although it is well known that the perception of brightness is highly dependent on color in many circumstances. Measurement of human response to color in terms of color matching is known as colorimetry [1].

The principles of photometry are the same as those for radiometry. Quantities are similar and have the same symbols. They can be distinguished by subscripts: e is for radiometric quantities and v is for the photometric ones. Being similar, however, they have different names and units. As the basic SI unit is *candela*, a unit of luminous intensity, the other photometric units are derived from it.

Since 1979, the definition of the *candela*, given by the General Conference on Weights and Measures (Conférence Générale des Poids et Mesures, CGPM), has been the following [7]: "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian".

It follows that spectral luminous efficacy for monochromatic radiation with frequency of 540×10^{12} hertz (0.555 μm) is exactly 683 lumens per watt, K_{max} = 683 lm/W = 683 cd sr/W.

2.3.1 Perception of light by the human eye

To understand the principle of conversions between radiant and photometric quantities, the effect of radiation on the human eye should be considered.

The human eye has two types of sensitive elements: cone and rod cells. The reaction of the eye in normal conditions is provided by cones and is called *photopic* vision. Perception of color is possible due to photopsin protein they contain. Rod cells are more light sensitive than cones, so in low light condition perception of light is provided by rod cells, containing light-sensitive protein, rhodopsin, which does not allow color distinguishing. This type of vision is called *scotopic* vision. In intermediate light conditions human vision is called *mesopic* vision and is not considered here.

In current practice, almost all photometric quantities are given in terms of *photopic* vision, even at low light levels. Quantities in *scotopic* vision are seldom used except for special calculations for research purposes.

The CIE (Commission Internationale de l'Éclairage) spectral responsivity of the human eye is shown in Fig. 2.5 (See also [8]). Spectral efficiency function for *photopic* vision is denoted as $V(\lambda)$ and for the *scotopic* one as $V'(\lambda)$. The maximum value of *photopic* vision responsivity is at 555 nm and 507 nm for *scotopic* vision.

Spectral luminous efficacy of radiation for *photopic* vision can be defined by the relation of spectral density of luminous flux and spectral density of radiant power per the same wavelength or spectral interval [9].

$$K_{\lambda}(\lambda) = \frac{\Phi_{\lambda v}(\lambda)}{\Phi_{\lambda e}(\lambda)} \tag{2.18}$$

Thus, relative spectral luminous efficacy of radiation for *photopic* vision is

$$V(\lambda) = \frac{K_\lambda(\lambda)}{K_{\max}(\lambda = 555nm)} \tag{2.19}$$

This quantity is expressed in relative units and its maximum value is 1 at the wavelength λ = 555 nm.

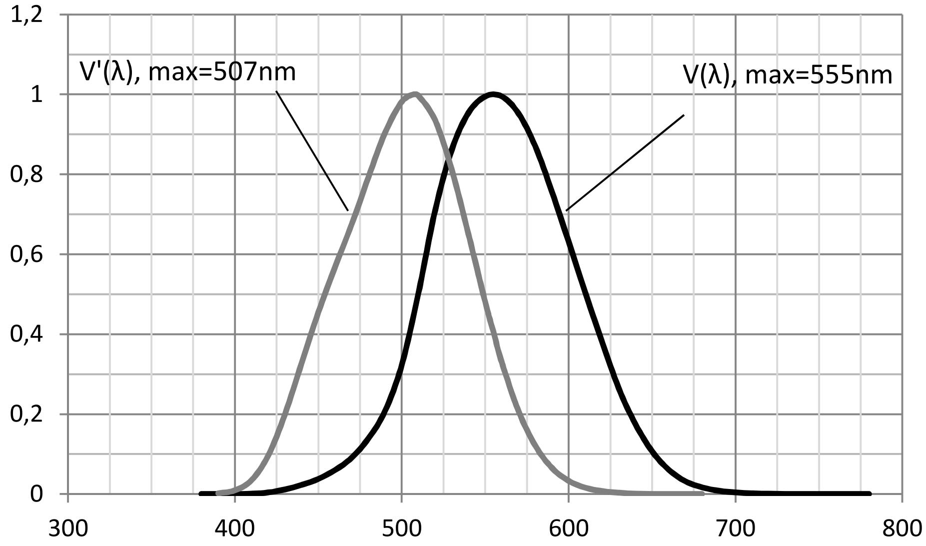


Figure 2.5 — CIE *V*(λ) and *V'*(λ) functions

Considering the above said, a photometric quantity X_v may be represented as a reduced quantity according to the expression (2.17), where $S'(\lambda) = V(\lambda)$ and $k = K_{\max} = 683$ lm/W.

Any photometric quantity is defined in relation to a corresponding photometric quantity by the equation

$$\Phi_v = K_{\max} \int_{380}^{780} \Phi_{e,\lambda} V(\lambda)\, d\lambda . \tag{2.20}$$

The constant K_{max}, relating the photometric and radiometric quantities, is called *maximum spectral luminous efficacy* (*of radiation*) *for photopic vision.* The K_{max} value is given by the 1979 definition of candela, that defines spectral luminous efficacy of light at a frequency 540 × 10^{12} Hz (at a wavelength 555.016 nm in standard air, near the maximum) to be 683 lm/W.

2.3.2 Luminous efficiency. Conversions of photometric units

Relation of luminous flux to radiant flux is presented as

$$\frac{\Phi_v}{\Phi_e} = \frac{K_{\max} \int_0^\infty \Phi_{e\lambda} V(\lambda)\, d\lambda}{\int_0^\infty \Phi_{e\lambda}\, d\lambda} = K_{\max} \cdot \kappa \tag{2.21}$$

The term $\int_0^\infty \Phi_{e\lambda} V(\lambda)\, d\lambda$ denotes the flux, that is effective for the eye, so the efficacy κ of a source for the eye is expressed as

$$\kappa = \frac{\int_0^\infty \Phi_\lambda V(\lambda)\, d\lambda}{\int_0^\infty \Phi_\lambda\, d\lambda} \text{ or also } \kappa = \frac{\int_0^\infty \varphi_\lambda V(\lambda)\, d\lambda}{\int_0^\infty \varphi_\lambda\, d\lambda}, \tag{2.22}$$

if we consider expression (2.16).

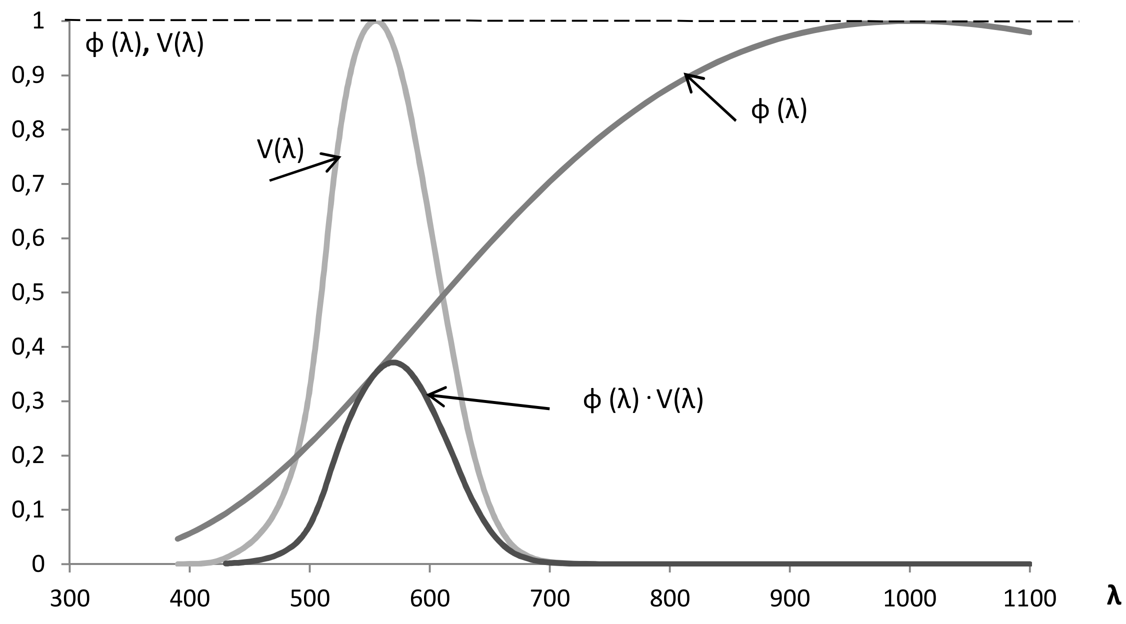


Figure2.6 — Luminous efficacy for the human eye

Expression (2.20) of unit conversion is valid for any radiometric unit X_e and photometric unit X_v (common units are listed in Table 2.2):

$$X_v = K_{\max} \int_{360}^{780} X_{e,\lambda} V(\lambda) d\lambda \text{, or } X_v = X_{e,\lambda} \cdot K_{\max} \cdot \kappa \qquad (2.23)$$

All relations between radiometric quantities, that were discussed in Section2.1 “Radiometric quantities and basic concepts”, are valid also for corresponding photometric quantities.

Thus, according to the above said, luminous energy Q_v is a photometric unit obtained according to the expression for reduced quantities:

$$Q_v = K_{\lambda \max} \cdot \int_0^{\infty} Q_{e\lambda} \cdot V(\lambda) d\lambda \text{, lm·s} \qquad (2.24)$$

where $Q_{e\lambda}$ is the luminous energy spectral density.

Definitions for each photometric quantity as for radiometric quantity are given above in Section 2.1, and definition formulae are listed in Table 2.1. Corresponding photometric and radiometric units are given in Table 2.2.

Table 2.1 — Photometric quantities

Name	Definition	Unit
Luminous flux	$\Phi_v = \dfrac{dQ_v}{dt}$	lm (lumen)
Luminous exitance	$M_v = \dfrac{d\Phi_v}{dA} = \int_{2\pi} L_v \cdot \cos\theta d\Omega$	lm m^{-2}
Luminous intensity	$I_v = \dfrac{\mathrm{d}\Phi_v}{\mathrm{d}\Omega} = \int_A L_v \cdot \cos\theta dA$	cd (candela)
Luminance	$L_v = \dfrac{d^2\Phi_v}{d^2G} = \dfrac{d^2\Phi_v}{dA \cdot \cos\theta \cdot d\Omega}$	cd m^{-2}
Illuminance	$E_v = \dfrac{d\Phi_v}{dA}$	lx (lux)
Luminous exposure	$H_v = \int_0^t E_v(t) dt$	lx·s

Table 2.2 — Quantities and units used in photometry and radiometry

Symbol	Photometric Quantity	Unit	Relationship with Lumen	Radiometric Quantity	Unit
Φ	Luminous flux	lm (lumen)		Radiant flux	W (watt)
I	Luminous intensity	cd (candela)	lm sr^{-1}	Radiant intensity	W sr^{-1}
E	Illuminance	lx (lux)	lm m^{-2}	Irradiance	W m^{-2}
L	Luminance	cd m^{-2}	lm sr^{-1} m^{-2}	Radiance	W sr^{-1} m^{-2}
M	Luminous exitance	lm m^{-2}		Radiant exitance	W m^{-2}
H	Luminous exposure	lx · s		Radiant exposure	W m^{-2}· s
Q	Luminous energy	lm · s		Radiant energy	J (joule)

Spectral densities are defined similarly as described in Section 2.2.

3. THERMAL RADIATION LAWS

Most natural bodies and several types of artificial sources used in optical-electronic devices are thermal radiators, i.e. their radiation spectrum is defined by temperature, and emittance is characterized by thermal radiation laws fora blackbody.

3.1 Kirchhoff's law

All bodies in nature emit radiation as their temperature is above absolute zero.

Kirchhoff's law of thermal radiation states: *For any material at all, radiating and absorbing in thermodynamic equilibrium at any given temperature T, for every wavelength λ, the ratio of emissive power to absorptive ratio has one universal value, which is characteristic of a perfect black body, and is an emissive power,* which is presented here by $M_{e\lambda T}$.

In other words, relation of spectral exitance to body absorptance is a function of wavelength and temperature and does not depend on the nature of the emitter.

$$\frac{M_{e\lambda_1 T_1}}{\alpha(\lambda)_{T_1}} = \frac{M_{e\lambda_2 T_2}}{\alpha(\lambda)_{T_2}} = \frac{M_{e\lambda T}}{\alpha(\lambda)_T} = f(\lambda, T), \tag{3.1}$$

where $M_{e\lambda T}$ and $\alpha(\lambda)_T$ are spectral exitance and spectral absorptance respectively at temperatures T_1, T_2, T and wavelength λ.

If an object absorbs all radiation (that means $\alpha(\lambda)_T = 1$), the object is called a blackbody. A blackbody is defined as an ideal body that allows all incident radiation to pass into it (zero reflectance) and that absorbs internally all incident radiation (zero transmittance). This must be true for all wavelengths and all angles of incidence. According to the definition of a blackbody, it is a perfect absorber, with an absorptance of 1.0 at all wavelengths and directions.

Since all real objects have an absorptance less than 1, they are nonblackbodies. So, the exitance of a real object is

$$M_{e\lambda_i T_i} = \alpha(\lambda)_{T_i} \cdot f(\lambda_i, T_i) = \alpha(\lambda)_{T_i} \cdot M^0_{e\lambda_i T_i}, \tag{3.2}$$

where $M_{e\lambda Ti}$ is spectral exitance of the blackbody at a temperature T_i.

Kirchhoff's law states that the absorptive power of a material equals its emissive power. If this were not true, a body would either emit more than it absorbs or vice versa, it would not be in equilibrium with radiation, and it would either heat up or cool off.

Radiation impinging upon a body is either reflected, transmitted, or absorbed. The fraction of incident radiation that is reflected ρ (reflectance), plus the fraction absorbed α (absorptance), plus the fraction transmitted τ (transmittance), equals one: $\alpha + \rho + \tau = 1$.

From Kirchhoff's law for a surface in radiative equilibrium, the fraction of the absorbed radiation equals the emitted fraction ε (emittance or emissivity). Therefore, the sum of reflectance, transmittance, and emittance must also be equal to one. If a body is opaque, the transmittance is zero, and the emittance is just equal to one minus the reflectance [1]: $\varepsilon = 1 - \rho$. According to Kirchhoff's law, bodies with high reflectivity (e.g. mirrors) are bad emitters, and vice versa.

3.2 Planck's law

Many attempts were made in the latter part of the nineteenth century and the early twentieth century to describe blackbody radiation mathematically, all doomed to failure before recognition of quantum concepts, developed by Max Planck in particular. Postulating quantum nature of radiation, Planck was able to derive an expression for blackbody radiation, which describes spectral radiance of a blackbody at a temperature *T* (K), as

$$M^0_{e,\lambda} = \frac{C_1}{n^2\lambda^5}\left[e^{\left(\frac{C_2}{n\lambda T}\right)} - 1\right]^{-1}, \; W/m^3, \qquad (3.3)$$

where

$C_1 = 2\pi hc^2 = 3.7417749\times10^{-16}$ W·m^2 – first radiation constant,
$C_2 = hc/k = 1.438769\times10^{-2}$ m·K^2– second radiation constant,
$h = 6.6252\times10^{-34}$ W·s2 – Planck's constant,
$c = 2.9979\times10^8$m/s- velocity of light in vacuum,
$k = 1.38042\times10^{-23}$W·s·K^{-1}–Boltzmann's constant,
n= 1.00028 –refractive index of standard air,
λ–wavelength,
T, K –absolute temperature of a blackbody.

Typical Planck's curves are presented in Fig. 3.1.

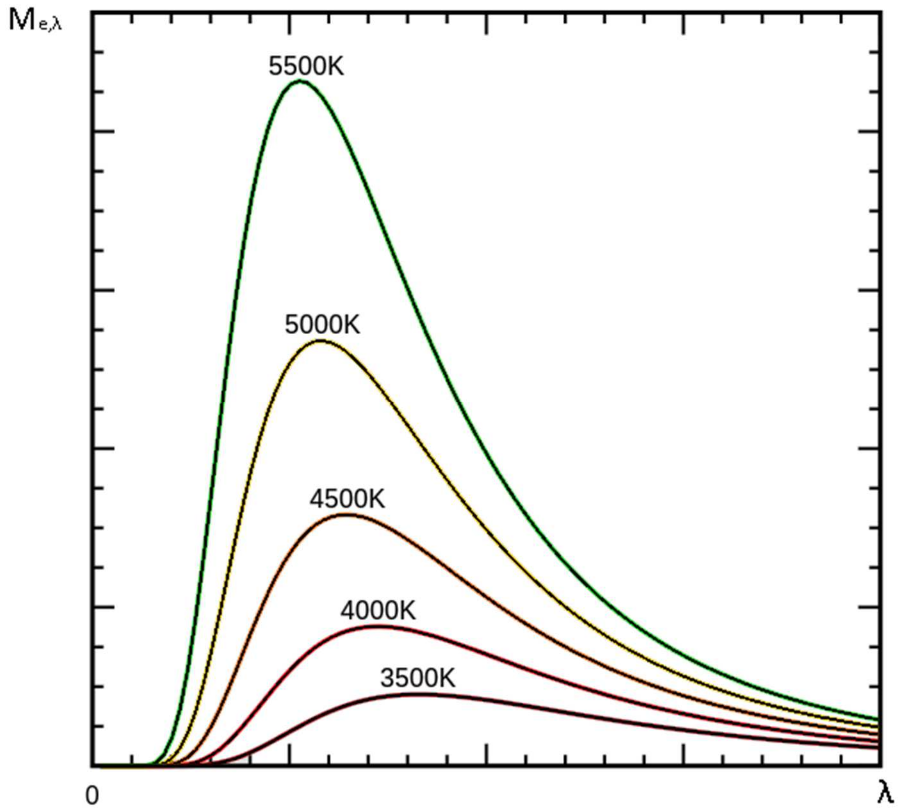


Figure 3.1 – Planck's curves at different temperatures

Two thermal radiation laws were derived from Planck's law, despite the fact that they had been empirically discovered before the invention of quantum theory. These are Stefan-Boltzmann law and Wiens' law.

3.3 Stefan-Boltzmann law

Planck's law integrated over all wavelengths (or frequencies) leads to Stefan-Boltzmann law, which describes temperature dependence of the total radiance of a blackbody.

$$M_e^0(T) = \int_0^\infty M_{e,\lambda} d\lambda = \sigma \cdot T^4 \text{, W/m}^2\text{,} \tag{3.4}$$

where $M_{e,\lambda}^0$ is spectral radiant exitance of a blackbody, and σ is Stefan-Boltzmann constant (5.67051×10^{-8} W·m^{-2}·K^{-4}). In other words, Stefan-Boltzmann law expresses the total radiant flux emitted from the surface of an object.

As part of radiation emitted by the environment, is absorbed by blackbody, the resulting emitted exitance in the thermal equilibrium state is

$$\Delta M_e^0 = \sigma \cdot \left(T^4 - T_{med}^4\right),$$

where T is the temperature of the emitter and T_{med} is the temperature of the medium.

3.4 Wien's displacement law

Taking the partial derivative of Planck's equation (3.3) with respect to temperature T, and setting the result equal to zero, the solution yields the relationship between the peak wavelength λ_{max} for Planck's radiation and temperature T(K), as given by

$$\lambda_{\max} = \frac{C_\lambda}{T}, \ \mu\text{m}.$$

This shows, that the peak wavelength of a blackbody radiation shifts to shorter wavelengths, as the temperature of the blackbody increases (Fig. 3.1). Value C_λ = 2987.8 µm·K is Wien's constant.

If we put λ_{max} into Planck's law (3.3), the peak spectral radiant exitance is

$$M_{e,\lambda\max}^0 = \frac{C_1 T^5}{(2898)^5}\left[e^{\left(\frac{C_2}{2898}\right)} - 1\right]^{-1} = C'_\lambda \cdot T^5, \ \text{W/m}^3, \tag{3.5}$$

where $C'_\lambda = 1.315 \times 10^{-5}$, W·m^{-3}·K^{-5} if λ is in meters. This equation is referred to as derivation from Planck's law.

Thus, the peak spectral radiant exitance is proportional to temperature in the fifth grade.

3.5 Universal representation of blackbody exitance

Planck's law leads to a "universal" representation of blackbody exitance in relative units, that would be identical for all blackbodies independent on their temperature.

If relative wavelength is denoted as $x = \lambda / \lambda_{\max}$, then exitance is represented by a function of x:

$$y(\lambda / \lambda_{\max}) = y(x) = M_{e,\lambda}^0 / M_{e,\lambda\max}^0, \tag{3.6}$$

with $M_{e,\lambda\max}^0$ defined by (3.5).

Planck's law then can be modified as

$$y = 142.32 \cdot x^{-5} \cdot \left(e^{4.9651/x} - 1\right)^{-1} \tag{3.7}$$

The graph of the function (3.7) is shown in Fig. 3.2.

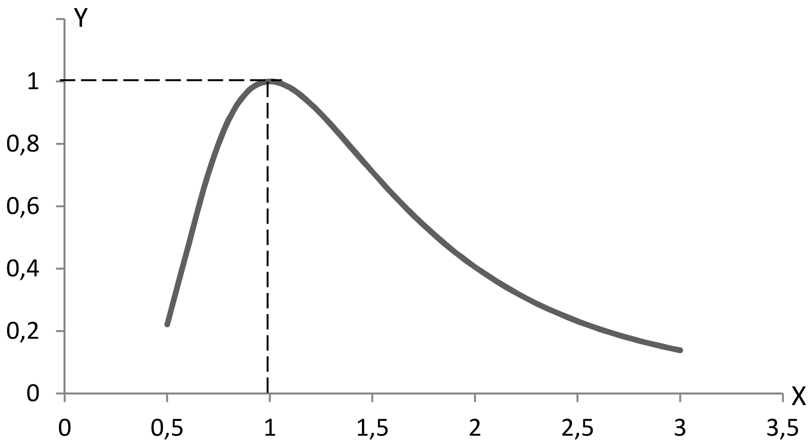


Figure 3.2 — Universal Planck's function $y = f\left(x\right)$

A portion of radiation *z* emitted in the band between $\lambda = 0$ to λ can be found as

$$z\left(\lambda / \lambda_{\max}\right) = z\left(x\right) = \frac{\int_0^{\lambda} M_{e,\lambda}^{0}(T)d\lambda}{\int_0^{\infty} M_{e,\lambda}^{0}(T)d\lambda} = \frac{\int_0^{\lambda} y(x)dx}{\int_0^{\infty} y(x)dx}.$$

To find a portion of radiation between λ_1 and λ_2, $\lambda_2 > \lambda_1$, the difference is found as

$$\frac{\Delta M_{e,(\lambda 1-\lambda 2)}^{0}}{M_e^{0}} = z\left(\lambda_2\right) - z\left(\lambda_1\right) = \frac{\int_0^{\lambda 2} y(x)dx - \int_0^{\lambda 1} y(x)dx}{\int_0^{\infty} y(x)dx},$$

where M_e^0 is defined by Stefan-Boltzmann's law (3.4).

3.6 Graybody and selective radiators

Imperfect emitters are called graybodies if their spectral shape matches that of a true blackbody, but the magnitude is less than that calculated with (3.3). They are called nonblackbodies if the spectral shape does not match that of a true blackbody. For a graybody, emittance does not depend on wavelength ($\varepsilon(\lambda)$=*const*), otherwise the object is a nonblackbody (see Fig. 3.3 (a)).

According to Kirchhoff's law(3.2), exitance spectral density of a graybody is expressed as

$$M_{e\lambda}^{c}=\varepsilon(\lambda,T)\cdot M_{e\lambda}^{0},\ \varepsilon(T)<1,$$

where $\varepsilon(\lambda,T)$ is exitance ($\varepsilon(\lambda)=\alpha(\lambda)$).

If exitance does not depend on wavelength ($\varepsilon(\lambda)=const$), the object is considered as a graybody. Otherwise, it is a nonblackbody, or a selective emitter ($\varepsilon(\lambda)\neq const$). The diagram of ε(λ) for different types of emitters is shown in Fig. 3.3 (b).

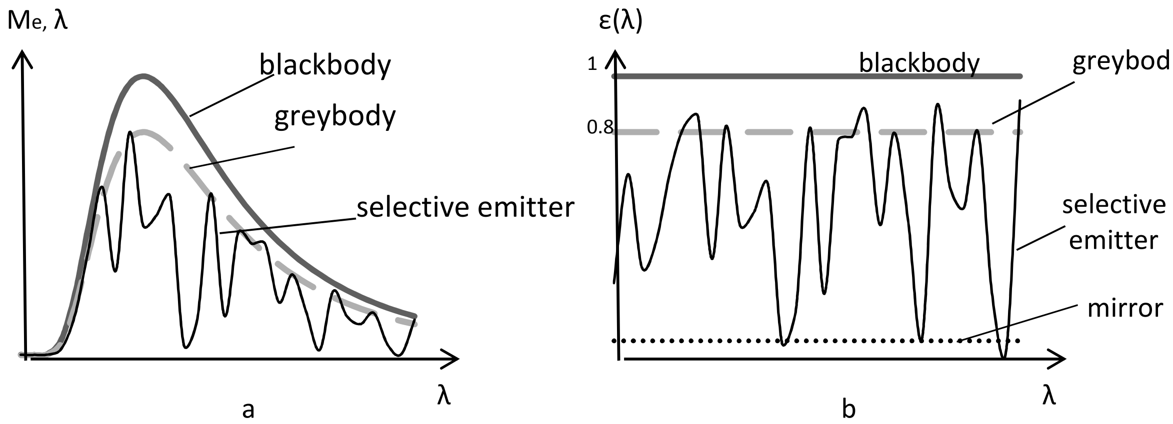


Figure 3.3 – (a) Radiant emittance spectral density for different emitter types; (b) emittance vs wavelength diagram for different emitter types

According to Stefan-Boltzmann law (3.4), full radiant exitance of a graybody is expressed as

$$M_{e}^{gb}=\varepsilon(T)\cdot M_{e}^{0}$$

3.7 Lambert's cosine law

In practice radiation sources are often considered as a Lambertian source. It means that their intensity depends on a radiation angle θ to the normal to the surface as

$$I(\theta)=I(0)\cdot\cos\theta .$$

Then, radiance is independent of the angle:

$$L_{e}(\theta)=\frac{I_{e}(\theta)}{A\cdot\cos\theta}=\frac{I_{e}}{A}=L_{e}=const .$$

Lambertian surface is a surface whose luminance (radiance) is the same in all directions of hemisphere above the surface.

Perfect (Reflecting/Transmitting) Diffuser is a Lambertian diffuser (Fig. 3.4) with reflectance (transmittance) equal to 1.

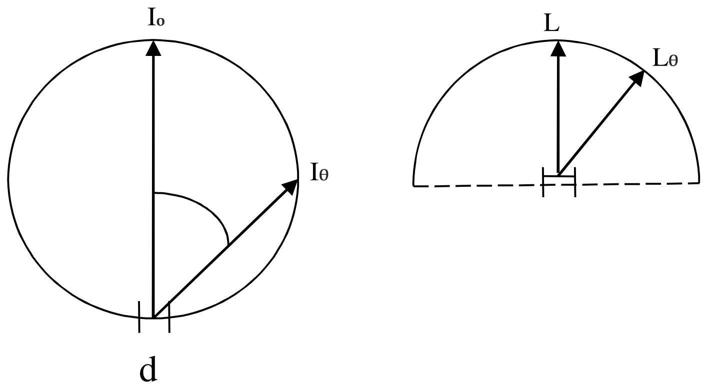


Figure 3.4 – Lambertian source

Based on Lambertian emitter properties, the relation between radiance and exitance is the following:

$$L = M / \pi$$

The expression is valid both for radiometric and photometric units. Natural rough surfaces can be considered as Lambertian within a specific angle (e.g. 0–40° for metal and 0–60° for dielectric).

3.8 Temperature Equivalents

Proper radiance of an object can be used for distant temperature measurements. Radiance spectral density of an object is compared to that of a blackbody. All instruments for this purpose must be calibrated with a blackbody.

Total radiation temperature *(T_R, K)* is the temperature of the Planckian radiator which has the same radiant exitance as the radiator considered. For a graybody radiation temperature is related to the true temperature as $T_R = T \cdot \sqrt[4]{\varepsilon}$ and is always smaller than true temperature.

Radiance temperature (or ***Brightness temperature***) (T_L, *K*) is the temperature of the Planckian radiator for which the radiance at the specific wavelength has the same spectral density as for the thermal radiator considered.

Color temperature (T_C, *K*) is the temperature of the Planckian radiator with radiation of the same chromaticity, as that of the light source in question. This term is commonly used to specify the colors of incandescent lamps, which chromaticity coordinates are practically on the blackbody locus.

Chromaticity is defined as radiance spectral density at two wavelengths. These are usually λ_1 = 0.655 µm and λ_2 = 0.467 µm. For a graybody T_C=T.

4. SOURCES

4.1 Classification of Optical Sources

All types of light sources can be grouped as natural and artificial. Natural sources are the Sun, the Moon, all objects of the environment as clouds, trees, buildings, animals, etc. Artificial sources are classified as follows [9]: 1) heat sources, 2) luminescent sources, 3) discharge sources, 4) lasers, 5) semiconductor sources (either light-emitting diodes or semiconductor lasers).

In a heat source, a flux and a spectrum of the source depend on its temperature. Light is emitted at spontaneous transition from higher to lower energy levels, and change of vibrational and rotational modes of atoms is the reason for IR radiation. Heat radiation has wide spectral range, it is incoherent and is emitted at all directions.

Luminescence occurs when electrons and atoms are excited by an electromagnetic field, then transit from higher to lower energy levels, emitting a portion of light. Luminescence radiation is also incoherent, emitted at all directions, but it has much narrower range than thermal radiation.

In discharge sources light is emitted due to an electrical discharge in noble gas, metal vapor, or mixed medium.

Laser radiation is caused by induced transition of electrons from higher to lower energy levels. It is coherent, monochrome and is emitted within small angle.

In semiconductor light sources radiation is connected with electron transition process at p-n junction.

Light sources can be classified by temporal parameters as continuous wave and pulse sources.

According to spatial diagram they are divided into directional and non-directional.

Worthing [10], suggested to answer the following questions that deal with functional and operational properties to select a source when designing a device:

1) Does it supply energy at such a rate or in such an amount as to make measurements possible?
2) Does it yield an irradiation that is generally constant or that may be varied with time as desired?
3) Is it reproducible?

4) Does it yield irradiations of the desired magnitudes over areas of the desired extent?

5) Does it have the desired spectral distribution?

6) Does it have the necessary operating life?

7) Does it have sufficient ruggedness for the proposed problem?

8) Is it sufficiently easy to be obtained and replaced, or is its purchase price or its construction cost reasonable?

4.2 Basic parameters of radiation sources

Sources of radiation may have different design and method of manufacturing, according to their applications. Light sources are optically characterized by their luminous spectrum (lumens as a function of wavelength), intensity (in candela), and efficiency (lumens per watt, lpw). For white light, correlated color temperature (CCT) and color rendering index (CRI) are derived from the spectrum of the source and are typically reported on the data sheets to give an estimate of its appearance and its ability to color render lit objects. Other source characteristics are cost, safety, government regulations, package size/type, lamp sockets, electrical driver requirements and constraints related to environment or operating conditions. Cost is defined in terms of luminous flux per currency unit per hour of use, replacement, and initial installation costs. The following artificial light sources, as incandescent, fluorescent, high-intensity discharge (HID), light-emitting diode (LED), laser, are discussed further.

4.3 Full radiator (blackbody)

A blackbody is considered as a standard radiation source, as its spectral density of radiant emittance is calculated with Planck's law. It is commonly used for detectors' certification and characterization, estimation of transmittance and absorption of materials, definition of monochromators' spectral transmittance, calibration of pyrometers and radiometers, characterization of various types of optical-electronic systems, etc.

Although a blackbody does not exist in nature, a radiation source with similar emitting properties can be created. The basic component is a cavity with a small exit opening. The cavity can be of various shapes, for example, conical, cylindrical, or spherical (Fig. 4.1). A blackbody implementation is shown in Fig. 4.2.

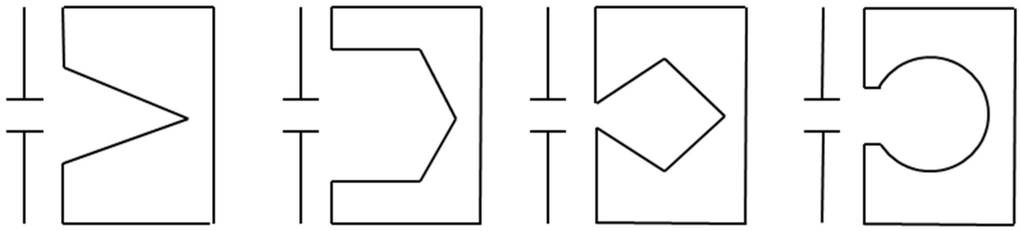


Figure 4.1 — Cavities of a blackbody model

The material of the cavity should have good thermal conductivity to obtain a constant temperature along its entire length. Thus, steel, aluminum and copper are commonly used for a blackbody model construction. The cavity surface is cavernous to obtain high emissivity. The temperature is controlled by a thermocouple. The cavity is heated by an electrical heater. Constant temperature is maintained by an automatic regulation system. The diaphragm before the exit hole is changeable and air- or water-cooled. In the implementation in Fig. 4.2 the diaphragm and the outer surface of the blackbody are water-cooled, that is why it has fittings for inlet and outlet of water.

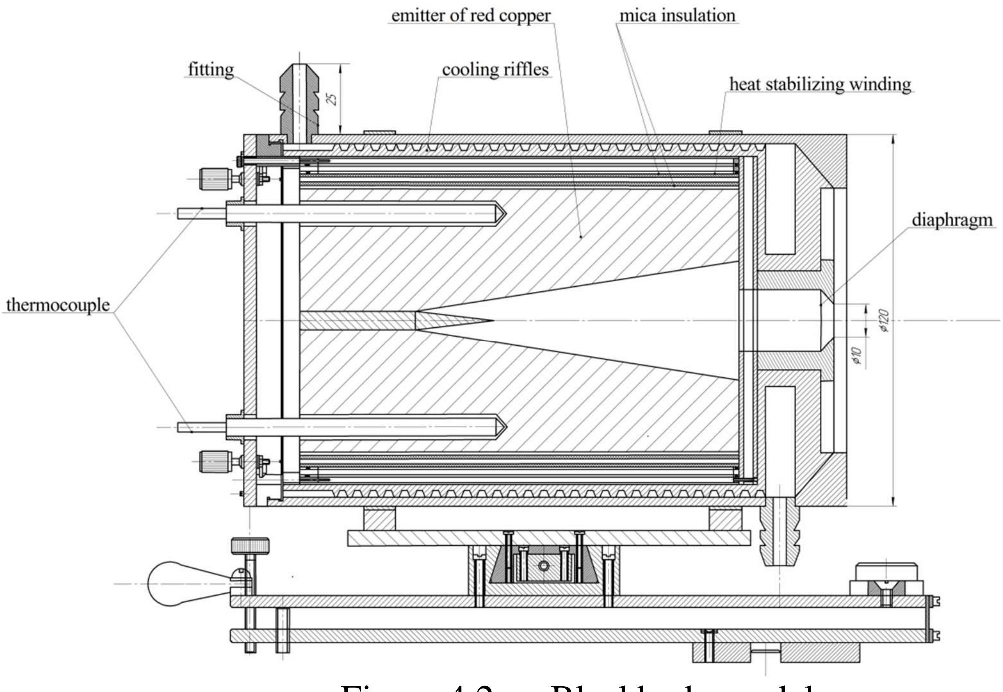


Figure 4.2 — Blackbody model

4.4 Incandescent lamp

The incandescent lamp is a light source that emits due to heating of a solid body up to a high temperature by current. A typical design of the lamp is presented in Fig. 4.3.

The first incandescent lamps in the nineteenth century were carbon-, iron-, osmium-, or tantanum-filament lamps. However, despite its low ductility tungsten has replaced all these filament materials because of its low vapor pressure, high melting point (3655 K), and strength. Today tungsten is typically alloyed with metals such as thorium and rhenium [11].

Modern incandescent lamps are filled with gas to increase the lifetime of the filament. These fill gases are generally mixtures of argon and nitrogen, with high percentage of argon for low-voltage lamps and very high percentages of nitrogen for high-voltage projection lamps. Occasionally krypton is added for still longer lifetime. None of these gases appreciably influences the spectral quality of the incandescent source.

Lamp filaments made of tungsten wire are sometimes used in a straight length but more often formed into a coil, or a coiled coil. The better (and more expensive) filaments have close-spaced coils to secure a bright, uniform light. It is important for photometric applications. Less expensive are the wide-spaced filaments, and these are entirely practical for many applications, such as slide projectors. The filament may also have a shape of a strip for measurement lamps.

Incandescent sources are similar to a blackbody, but not exactly as intense. The spectrum of an incandescent lamp is mostly Near-IR, that is why it has low efficiency $K = \Phi_v / \Phi_e$ (lm/W).

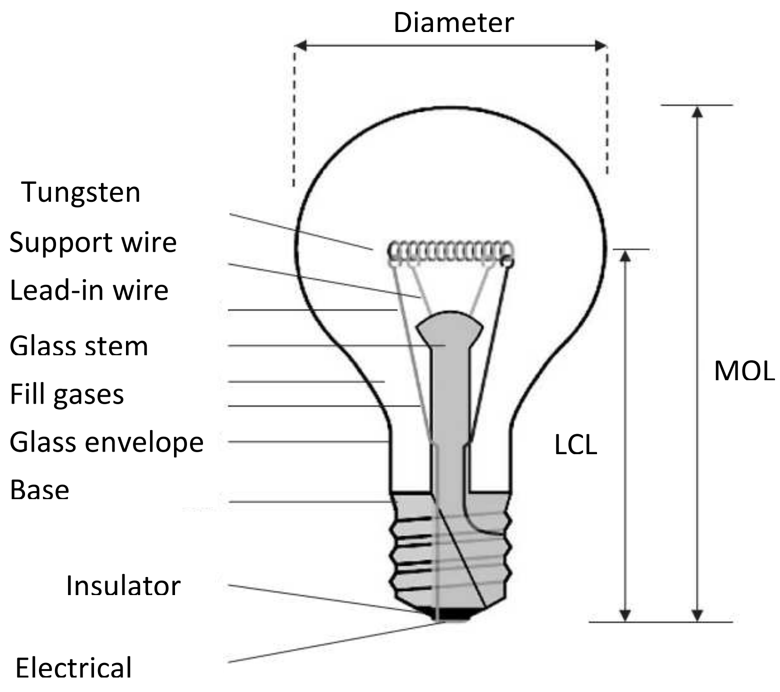


Figure 4.3 – An incandescent bulb (MOL – maximum overall length, LCL – light center length)

The advnatages of incandescent lamps are as follows: there is almost no run-up time, they are easy to be connected into a circuit, have a continuous spectrum, a proven manufacturing technology for lamps of wide power range, low cost, and high reliability. The drawbacks are low luminous efficiency (1–3%), heat emission, a spectrum different from the solar one.

For some applications, such as projection or optical instrumentation, the filament is packed into a specific shape to provide a uniform luminosity and maximum brightness. The filament position is also important for such applications and thus strictly defined.

4.5 Halogen lamp

The halogen lamp is also a type of incandescent lamp, however, the principle differs from the one described above. Tungsten-halogen lamps contain a small amount of halogen, such as bromine, chlorine, or iodine. Halogen teams with tungsten to create the halogen regenerative cycle — particles of tungsten thrown off by the filament combine with halogen to form a gas that is attracted to the hot filament and attaches to the filament. However, the lost particles of tungsten do not redeposit in exactly the same place, so the filament is modified, spotting and eventually failing as before. The important feature of tungsten-halogen lamps is that particles of tungsten collected by the filament are prevented from depositing on the glass envelope. Thus, the lamps do not form black coating on the inner surface.

Halogen lamps must run hot to keep the regenerating cycle going, not less than 573 degrees K. At lower temperatures, tungsten will deposit on the bulb envelope instead and lead to lamp blackening and filament thinning, a common failure mode of incandescent lamps. For comparison, a 100-watt household lamp is never hotter than about 500 degrees K, meaning that this temperature is too low for a halogen lamp. Normal glass does not stand the higher temperature, so all halogens are made of special heat-resistant glass or quartz.

Halogen lamps have better efficiency (26–30 lm/W vs. 13–18 lm/W for common lamps) at the same temperature, e.g. at 3400 K, and a longer life, compared to tungsten-filament lamps.

4.6 Nernst glower

The Nernst glower is usually constructed in the form of a cylindrical rod or tube from refractory materials (usually zirconia, yttria, beria, and thoria) in various sizes, typically from 1 to 3 mm diameter by 30 mm. Platinum leads at the tube ends conduct power to the glower from the source. The color temperature of the glower can be from 1500 to 1950 K. Since the resistivity of the material at room temperature is quite high, the working voltage is insufficient to get the glower started. Once started, its negative temperature coefficient-of-resistance tends to increase current, which would cause its destruction, so that a ballast in the circuit is required. Starting is effected by applying external heat, either with a flame or an adjacent electrically heated wire, until the glower begins to radiate.

Since the Nernst glower is made in the form of a long thin cylinder, it is particularly useful for illuminating spectrometer slits. Its useful spectral range is from the visible region to almost 30 μm, although its usefulness compared with other sources diminishes beyond about 15 μm. As a rough estimate, the radiance of a glower is nearly that of a greybody at the operating temperature with an emissivity in excess of 75 percent, especially below 15 μm.

4.7 Globar

The globar is a rod of bonded silicon carbide usually capped with metallic caps which serve as electrodes for the conduction of current through the globar from the power source. The current causes the globar to heat, yielding radiation at a temperature above 1000°C. A flow of water through the housing that contains the rod is needed to cool the electrodes (usually silver). This complexity makes the globar less convenient to use than the Nernst glower and thus more expensive. This source can be obtained already mounted, from a number of manufacturers of spectroscopic equipment. Both the globar and the Nernst glower are used in spectral instruments as they provide radiation spectrum close to the greybody.

4.8 Fluorescent lamp

The fluorescent lamp is a luminous source based on light emission by excited states of phosphors, a phenomenon known as *fluorescence*. These phosphors are typically excited by UV emission due to spectral line transitions across gases such as mercury vapor and/or rare gases such as Xe and Ar. Most commonly available fluorescent lamps are mercury-vapor-based, although mercury-free fluorescent sources are available. Phosphors that are excitable by visible light are now available. Such phosphors are also being used for LED-based light sources to produce white light. Fluorescent lamps are actively replacing incandescent light sources and in many cases are themselves being replaced by LEDs. [1]

A fluorescent lamp (Fig. 4.4) consists of a closed tubular glass envelope coated with fluorescent material and filled with low-pressure mercury vapor, electrodes at each end of the tube, and a ballast to provide high-strike voltage across the electrodes and limit the current during operation. A high-strike voltage across the electrodes initiates a gas discharge in the mercury vapor with light emission across various wavelengths. The UV emission lines of mercury, mostly at 254 nm, excite the phosphors coated on the inside of the tube, cause them to fluoresce and lead to emission in the visible band. The fill gases consist of mercury vapor at low pressure (10^{-5} atm) for UV emission and mixtures of inert gasses such as argon, krypton, neon, or xenon at a relatively higher pressure (10^{-3} atm).

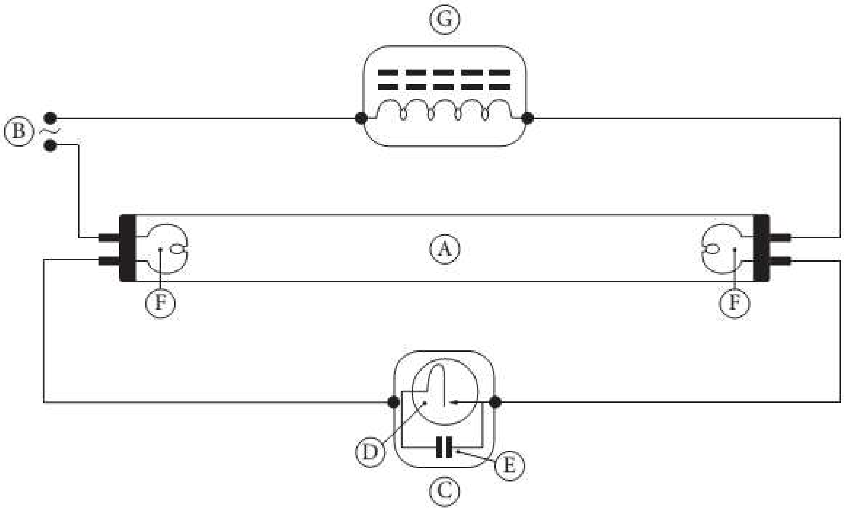


Figure4.4 – A preheat fluorescent lamp circuit using an automatic starting switch. A—fluorescent tube with fill gases, B—power, C—starter, D—switch (bimetallic thermostat), E—capacitor, F—filaments, and G—ballast

The lamp electrodes are coated with materials such as oxides of barium, calcium, and strontium to provide low-temperature thermionic emission (electron emission from a heated electrode). Under a potential, these electrons accelerate and ionize the inert gas atoms by impact ionization. Each ionization event generates more electrons that are available to accelerate and further ionize leading to an avalanche that rapidly lowers the gas conductivity. Eventually mercury atoms are ionized. The operating voltage drops and a steady current is established. UV is emitted by transitions across the excited states of mercury atoms. The electrodes can be operated in either of the two modes: cold cathode (arc mode) or hot cathode (glow mode).

The primary functions of the lamp ballast are to provide a high-strike voltage to start the lamp, give regulated current supply during lamp operation and sometimes provide for cathode preheating for rapid restart applications. Starter circuitry is often deployed to preheat the electrodes.

Lamp failure mode consists of thermionic emission electrode coating degradation (a function of strike voltage and the number of strikes), phosphor degradation, mercury loss (diffusion or absorption by lamp materials) and ballast malfunction.

4.9 High-Intensity Discharge (HID) and Low-Pressure Sodium (LPS) Lamps

These sources emit light across the spectral line transition of enclosed gases by electrical discharge. The source spectrum also includes background thermal radiation due to the heated electrodes and plasma. These sources are similar to fluorescent sources in basic physics involving discharge and emission of light in the UV and visible band as a result of transitions between the excited states of gas atoms. Unlike fluorescent lamps, the electrodes are separated by less than 1 mm up to a few inches. The enclosed gases are at a pressure that is three orders of magnitude higher than in fluorescent sources. As a result, HID sources are far brighter than fluorescent sources with much higher lumen output. The following types of HID lamps are commonly available: mercury vapor (Hg), metal halides (MH), high-pressure sodium (HPS), and ceramic metal halides (CMH). CMH combines the advantages of MH and HPS technologies. Each HID lamp technology has very different performance and operating characteristics. An LPS lamp is similar to HID lamps in construction and operation with some differences that are identified as we describe the HID lamps below. Fig. 4.5 describes the construction of various HID and LPS lamps [1].

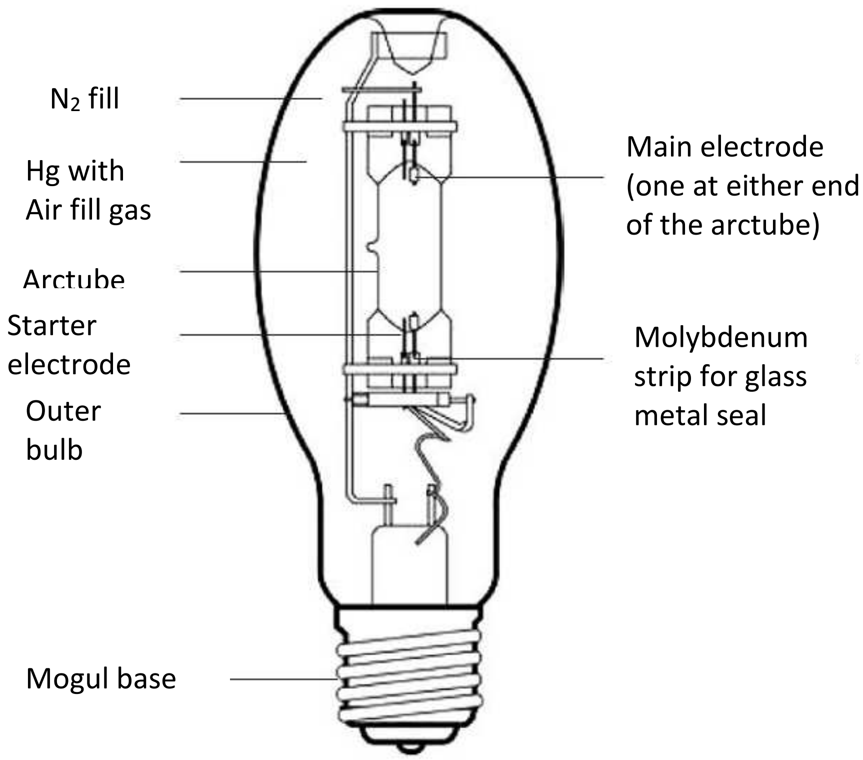


Figure4.5 – Mercury lamp construction

An HID lamp consists of two glass envelopes: inner and outer. The inner glass envelope or the arc tube is made of quartz for MH and Hg and alumina ceramic for HPS, LPS, and CMH lamps. The arc tube houses the discharge gases at high pressure (several atmospheres) and the tungsten electrodes. The outer glass envelope is made of borosilicate and sometimes with soft glass in Hg lamps. It absorbs UV and insulates the arc tube from outer convection currents and from large ambient temperature ranges. It houses the lead-in wires, circuitry to help initiate the high-voltage discharge, getters in case of MH to absorb impurities and has a vacuum (HPS) or low-pressure nitrogen (MH and Hg) to prevent shorting of the lead-in wires. The outer-envelope Hg lamp is sometimes coated with phosphors to provide white light at high CRI and CCT like in regular fluorescent lamps.

An LPS lamp is similar in construction and operation to HID lamps. Key differences are lower arc tube pressure (0.7 atm), long arc length with a U-shaped arc tube. The arc tube gases include odium vapor and small amounts of Ne, Ar, or Xe as startup gases.

HID lamps require several minutes of start-up time (time to reach stable output) and restrike. A long start-up is due to the time taken to reach a stable operating temperature and pressure within the arc tube. The restrike time interval results from the necessity to have low pressure inside the arc tube for arc initiation. Complex ballasts are needed to provide startup, restrike, and stable operation with constant current. To improve startup, restrike, and operations at low voltage, a high voltage-low current pulsed start is used. Sometimes, multiple arc tubes within the outer bulb envelope are used to provide faster restrike. Only one arc tube operates at a time in such lamps. Xe-based HID lamps are capable of instant-on and restrike. Automotive HID lamps use Xe with metal halides to improve the start and restrike times dramatically.

Physical orientation of HID lamps such as Hg and MH during operation is far more important than with the other lamps. Due to convection, within and outside the lamp, different portions of any lamp, not just HID, are heated to different temperatures. The lamp engineering must take this into account and ensure that the hottest regions do not constitute a failure mode either by design or by providing instructions to the user for best operating configuration. In MH and Hg HID, the high convection roll within the long arc tube has an overwhelming effect on the arc shape and position under gravity. It can make the arc shape curved and lead to nonuniform degradation of the electrode tips and impact the light output, lifetime, and light distribution patterns. HPS lamps, however, can be operated in any position primarily due to a compact arc tube at high gas pressure (5 to 27 atmospheres).

Lamp degradation and failure is due to electrode degradation by evaporation, arc tube blackening is due to electrode material deposition, loss of gas pressure, and selective diffusion of gases lead to change in the lamp color. Arc tube blackening also leads to the rise in the arc tube temperature causing an analogous rise in pressure and operating voltage. The effect is seen well in HPS, where lamp cycling occurs: as the lamp cools down, it is able to restrike but after some time temperature rises to the point that it shuts down.

4.10 Semiconductor light sources: LED and IR diodes

Electroluminescent sources are materials that emit light in response to an electric field. Examples of such materials include

- powdered ZnS doped with copper or silver,
- thin film ZnS doped with manganese,
- natural blue diamond (pure diamond with boron as a dopant),
- III-V semiconductors or inorganic LED materials such as AlGaAs,
- phosphors coated on a capacitor plane and powered by pulsating current,
- organic LED (OLED) also known as light-emitting polymer or organic electroluminescent.

Electroluminescent sources can operate at low electrical power with simple circuitry. They are commonly used for providing illumination across small regions such as indicator panels. LEDs are already a major lighting source that is rapidly replacing incandescent and fluorescent light sources.

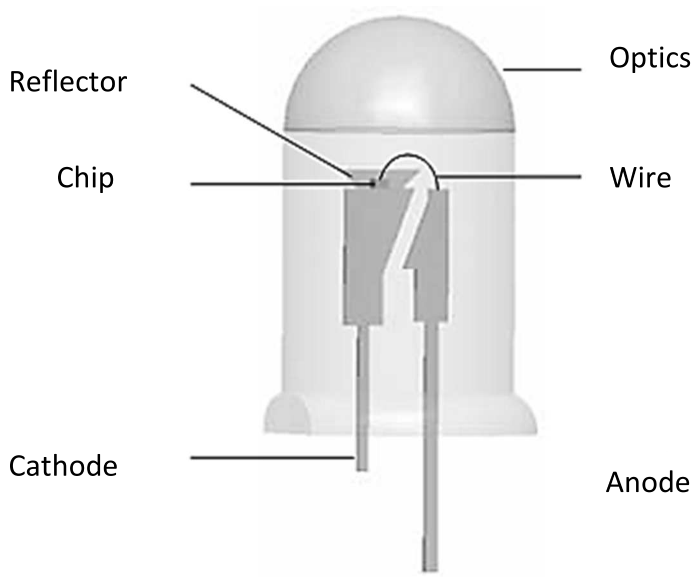


Figure4.6 – Structure of a simple packaged LED

LEDs emit light by electron-hole pair recombination across the pn-junction of a diode. The wavelength of the emitted light corresponds to the band gap (energy gap between valence and conduction bands) across which the electron hole pair is created. The degeneracy in the valence and conduction bands leads to a closely spaced band of wavelengths that constitute light from the LED. Narrow spectral bandwidth enables applications that require saturated colors. Although LEDs are not available for every desired color, it is possible to combine LEDs of different colors to create any color within the color gamut defined by these LEDs. As such, color mixing has become an important field. LEDs emitting in specific bandwidths can be combined with sources with continuous spectra to either enhance a certain spectral region or to provide an easy dynamic color control. Lightguides are one of the easy methods to combine multiple LEDs. Lightguides with rippled surface texture along the cross section are particularly efficient in combining multiple colors with excellent uniformity in a short path length.

LED lamps may have an array of small LED chips or a single large chip to achieve the desired power levels. The directionality is controlled by the appropriately mounted optics. DC operation of LEDs makes them flicker free sources. Fig. 4.6 shows the structure of a simple packaged LED.

LED packages come in various sizes and shapes. Surface mount LEDs (SMD) have minimum packaging and are almost a bare die. LED packages are also offered in multicolored die formats. A diagram in Fig. 4.7 demonstrates dependence of light diagrams of LEDs on the shape of the package.

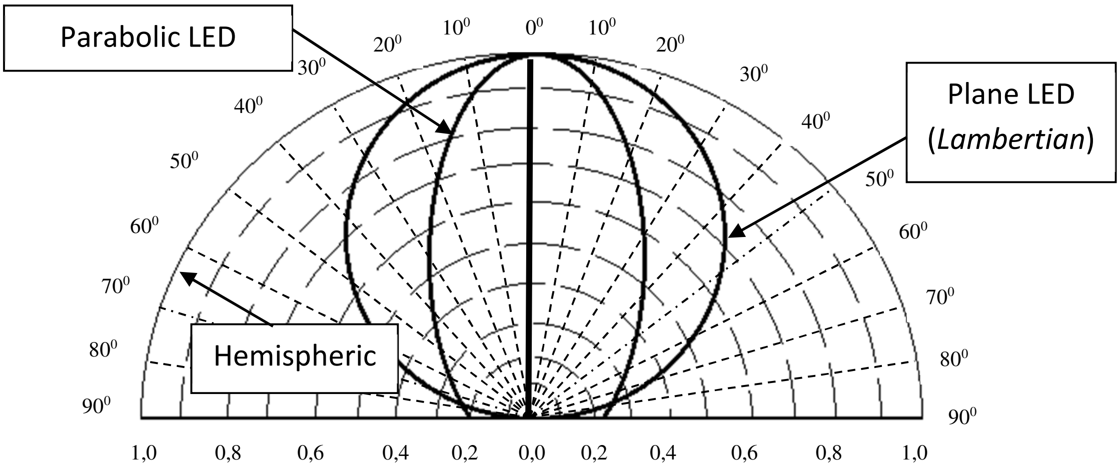


Figure4.7 – Light diagram of LEDs for various package types

There is a continuous push to improve the LED efficiency and brightness while keeping the lifetimes high. High brightness LEDs became possible due to large area chips, efficient heat extraction and better light extraction from the chip. Internal quantum efficiency of LEDs can be increased by placing emitters inside a cavity to increase the radiative recombination rate. Because of high internal Fresnel reflections and lateral waveguiding, a lot of light fails to exit the chip. Techniques such as texturing the surface with photonic crystals assist in increasing light extraction from large dies. Fig. 19 shows the internal structure of a photonic crystal LED.

Organic LEDs (OLEDs) in contrast to inorganic LEDs are size-scalable light sources with richer color spectra. OLEDs can be used to create flexible transparent lighting solutions as they can be printed on a malleable substrate with transparent electrodes. Currently OLEDs are being used for displays and are competing with LCD flat panels. Conceptually, OLEDs are similar to inorganic semiconductor based LEDs. An OLED deploys layers of organic materials on polymer substrates to form conductive and emissive layers connected to a cathode and anode respectively. Much of OLED research is aimed at making them brighter and longer lasting.

LED failure causes include

- damage due to degradation of the active layers with time (spontaneously or in operation);
- plastic package degradation due to ambient UV;
- electrostatic discharge;
- current crowding or inhomogeneous current distribution across the junction leading to hot spots;
- thermal stresses causing rupture of the LED package;
- diffusing of the metal contact material into the die material at high currents;
- high output leading to facet melting and phosphor degradation in white LEDs;
- and degradation of organic layers in OLEDs.

Blue LED Technology

Blue emitters have been commercially available for more than a decade, but have only begun to have a significant impact on the market in the last few years. SiC is the leading technology for blue emitters with a quantum efficiency of about 0.02 percent and 0.04 lm/A luminous performance. SiC devices are not much used due to their high price and relatively low performance efficiency. Other approaches for making blue LEDs are the use of II–VI compounds such as ZnSe or the nitride system GaN, AlGaN, or AlGaInN. It has been difficult to make good *p-n* junctions in these materials. Recently improved *p-n* junctions have been demonstrated in both ZnSe and GaN.

Device performance is still in the 0.1-lm/A range and reliability is unproven. However, this recent progress is very encouraging for blue-emission technology and could lead to a high performance device in the next few years. Both ZnSe and the nitride systems have a major advantage over SiC because they are direct bandgap semiconductors, so a much higher internal quantum efficiency is possible. However, it is difficult to find suitable lattice-matched substrates for these materials.

White Light LED

Over the years, a variety of materials for LEDs have been used to get a higher efficiency and different colors across the visible spectrum. LED technology is fast evolving with ever increasing brightness, lifetime, colors, materials and decreasing costs.

Most lighting applications require white light. Some processes for making white-light LEDs are listed below:

- Arrays of small red, green, and blue dies placed in close proximity in a single LED package. Good color mixing takes place in angular space.
- Color-mixing of red, green, and blue colors using lightguide or other optical means.
- Phosphor excitation by blue or UVEDs.
- Novel techniques like quantum dot blue LEDs or homoepitaxially grown ZnSe blue LEDs on a ZnSe substrate. The active region emits blue light while the substrate emits yellow light.

4.11 Lasers

Lasers are devices that amplify the intensity of light to produce a highly directional, high-power beam with a very pure frequency or wavelength. Lasers produce powers ranging from nanowatts to 10^{21} watts for very short bursts. They produce wavelengths or frequencies ranging from the microwave and infrared through the visible, ultraviolet, vacuum ultraviolet regions into the soft-X-ray spectral regions. They generate the shortest possible bursts of light of approximately 5×10^{-15} sec. [11].

A typical laser device (Fig. 4.8) consists of an amplifying or gain medium, a pumping source to input energy into the device, and an optical cavity or mirror arrangement that reflects the beam of light back and forth through the gain medium for further amplification. An output laser beam is obtained by allowing a small portion of light to escape by passing through one of the mirrors that is partially transmitting.

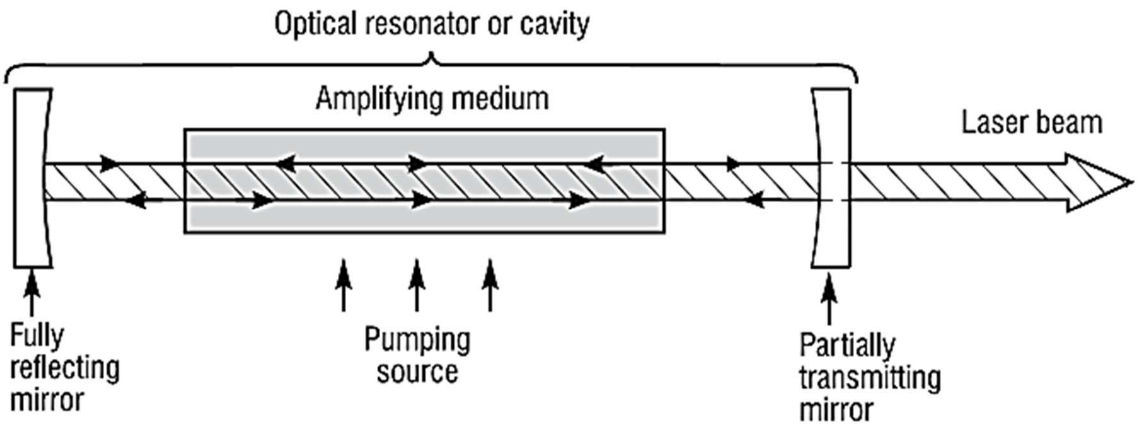


Figure 4.8 – Basic laser components including gain medium, pumping source, and mirror cavity

4.11.1 Laser gain medium

Nearly all lasers produce radiation because of electrons jumping from an excited energy level within radiating species to a lower-lying energy level radiating light that contributes to the laser beam. Those radiating species can include:

atoms, such as in the red helium-neon (HeNe) laser, the visible and ultraviolet argon ion and helium-cadmium (HeCd) lasers, and the green and yellow copper vapor lasers (CVL);

molecules, such as in the infrared carbon dioxide (CO_2) laser, ultraviolet excimer lasers such as ArF and KrF, and the pulsed N2 laser;

liquids, containing various organic dye molecules dilutely dissolved in various solvent solutions;

dielectric solids, involving neodymium atoms doped in YAG or glass to make the crystalline Nd:YAG or Nd:glass lasers;

semiconductor materials, such as gallium arsenide or indium phosphide crystals or various mixtures of impurities blended with those and other semiconductor species. Each of the above species contains its own lowest energy level referred to as the ground state in which the electrons predominantly reside at room temperature, as indicated by level 0 in Fig. 4.9. [11]

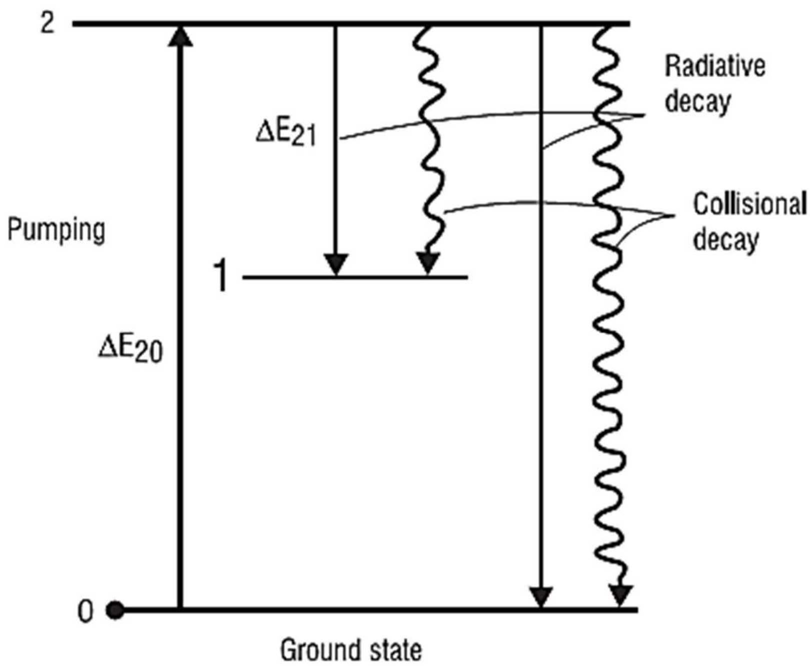


Figure 4.9 – Simplified energy diagram of an atom showing excitation and emission processes

The electrons are moved to higher (excited) levels, such as 1 and 2, by means of various pumping processes that are described in the next section. They then decay back to lower levels within a period called the lifetime of the level, and eventually find their way back to the ground state when the pumping source is removed. There are three types of interaction of light beams with atoms that have electrons residing in various energy levels. Examples of those are depicted in Fig. 4.10. First, an electron residing in level 2 can spontaneously jump to level 1, radiating a photon of light. That process is known as *spontaneous emission,* as indicated in Fig. 4.10a. Most excited energy levels undergo spontaneous emission. Each level has a specific lifetime τ over which it will remain in that level before decaying to a lower-lying level. The photon radiated during spontaneous emission has the exact wavelength λ_{21} and frequency ν_{21} corresponding to the difference in energy ΔE_{21} ($\Delta E_{12} = h\nu_{21} = hc / \lambda_{21}$) of the two involved energy levels (1 and 2 in this case) according to the relationship, in which h is Planck's constant such that h = 6.63×10^{-34}joule-sec and c is the speed of light, $c = 3 \times 10^{8}$m/sec. Because different materials have different energy-level arrangements, they radiate at different wavelengths, and thus emit different colors or frequencies of light that are specific to the material.

The second process is *absorption*, shown in Fig. 4.10b, which occurs if the atom has its electron in level 1 of Fig. 4.10 and a photon of light of wavelength λ_{21} collides with the atom. During the collision, the photon is absorbed by the atom and the electron is moved up to the higher energy level 2. It can happen from any energy level occupied (generally the ground state) and always boosts the atom to a higher-lying level while eliminating the photon. This often results in heating of the absorbing material.

The third process, shown in Fig. 4.10c, is referred to as *stimulated emission*. It results when an electron is in a higher-lying level, such as level 2 in Fig. 4.9, and a photon of light of wavelength λ_{21} collides with the atom. During the collision the photon stimulates the atom to radiate the second photon having exactly the same energy ΔE_{21}, as that of the incident photon, and traveling in exactly the same direction in order to satisfy the laws of conservation of energy and momentum. Hence, one photon leads to two identical photons, which, in effect, leads to an amplification process. The photon has been gained at the expense of the energy loss stored within the atom.

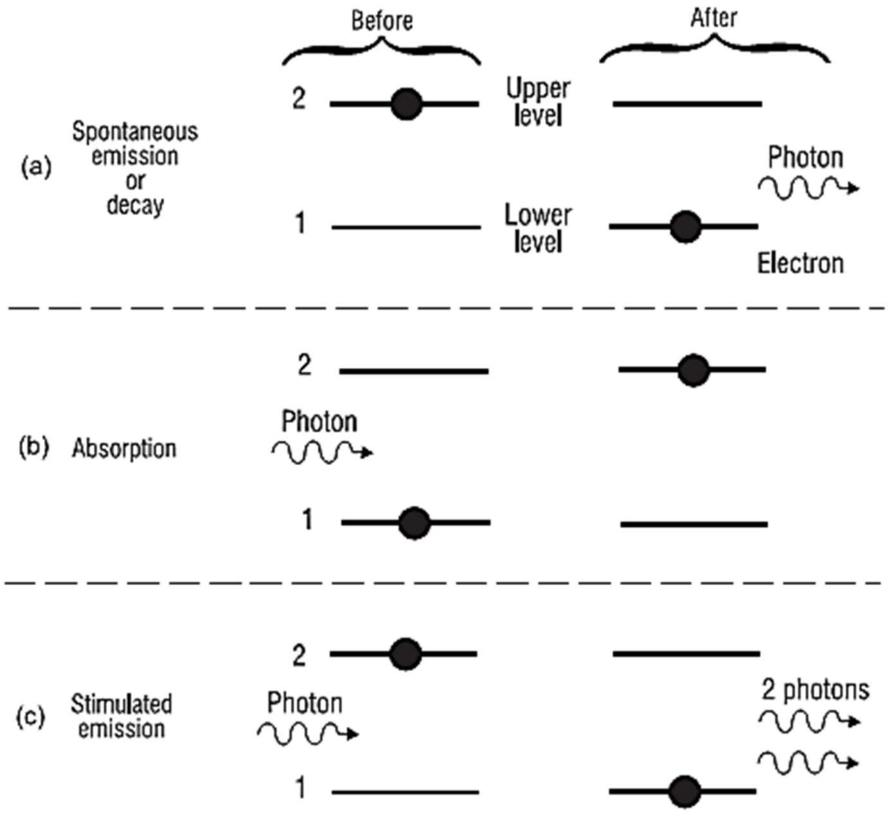


Figure 4.10 – The three radiation processes that can occur when light interacts with matter (atoms)

4.11.2 Laser pumping sources

Laser pumping sources are the means by which energy is transferred into the laser gain medium to produce the required population inversion ΔN_{21}.

Electron pumping. Electron pumping is used primarily in gaseous or semiconductor gain media. In semiconductors, the electrons flow through the semiconducting material by applying voltage across the pn-junction with positive voltage on the side of the p-type material.

Optical pumping. Optical laser pumping is generally applied to the pumping of liquid (dye) lasers and to dielectric solid-state lasers and is provided by either flash lamps or other lasers. The most common types of flash lamps used for pumping lasers are narrow cylindrical quartz tubes with metal electrodes mounted on the ends, filled with gaseous species such as xenon that serves as the radiating material within the lamp [11].

4.11.3 Laser beam properties Laser beam properties such as direction and divergence of the beam, beam profile, and wavelength and frequency characteristics of the laser within the wavelength region of the laser gain bandwidth are largely determined by laser mirrors. The factors determining those properties include mirror curvature, surface quality, and reflectivity as well as separation and location, assuming the mirror holding structure to be secure and vibration-free. The unique electromagnetic wave properties produced by mirrors are referred to as modes [11].

Longitudinal cavity modes. When the beam is developing within the mirror cavity, traveling back and forth, some wavelengths within the laser gain bandwidth tend to be more enhanced than others. These are wavelengths (or frequencies) in which the light beam in the cavity forms a standing wave. Such an effect occurs when an exact number of half-wavelengths of light fit within the separation distance between the mirrors. Typically, there will be several hundred thousand wave peaks for each standing wave that occur within the cavity. Hence, each standing wave must have wavelength such that an integral number of oscillating waves fits in the space separating the mirrors. If more than one standing wave is present, each standing wave (longitudinal mode) will be separated in frequency from the next one by fixed exact amount that depends upon the laser cavity length *d*. That frequency separation Δν between longitudinal modes is obtained by dividing the speed of light *c* by twice the cavity length *d*, or

$$\Delta\nu = c/(2d). \tag{4.1}$$

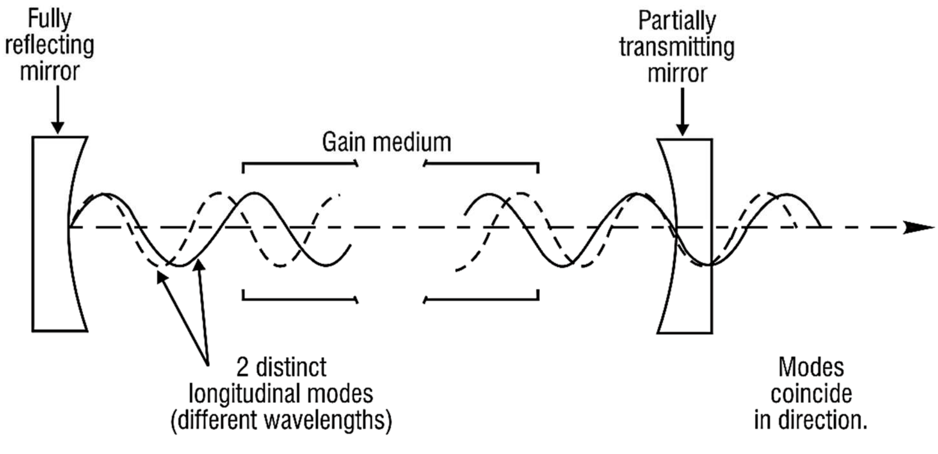


Figure4.11 – Two distinct longitudinal modes operating simultaneously in the same laser cavity

Each discrete standing wave is referred to as a longitudinal mode associated with a laser cavity. Fig. 4.11 shows two such modes within the cavity. There will always be at least one longitudinal mode, and there could be many more, depending on the frequency or wavelength bandwidth of the laser gain medium.

If more than one longitudinal mode is being generated, they will travel in the same direction, and their color will be indistinguishable, because their wavelengths (frequencies) are similar. To distinguish a mode, a spectrum analyzer is used.

Transverse modes. The presence of more than one longitudinal mode involves many light beams traveling the same path through the amplifier but differing in wavelength depending on the total number of wave cycles that fit between the mirrors. Contrary to this, different transverse modes involve slightly different optical paths through the amplifier, and thus have slightly different directions when they emerge from the laser, as shown in Fig. 4.12. Because of different optical path lengths, they also have slightly different frequencies. Each of these stable modes evolves because the light traveling that particular pathway recurs exactly from one round trip of the beam to the next, therefore developing into a steady beam. Each transverse mode traveling over its unique path might also consist of several longitudinal modes separated in frequency according to equation (4.1) [11].

The lowest-order transverse mode, known as the TEM_{00} mode, travels down the central axis of the laser gain medium. Higher-order modes have slightly diverging beams as shown in Fig. 4.12. The TEM_{11} mode, for example, if it were the only mode present, would appear as a doughnut-shaped beam when projected onto a screen. Complex patterns can be present if several transverse modes are operating. In most cases, closely located transverse modes differ in frequency by a smaller value than do adjacent longitudinal modes that follow the same path through the amplifier.

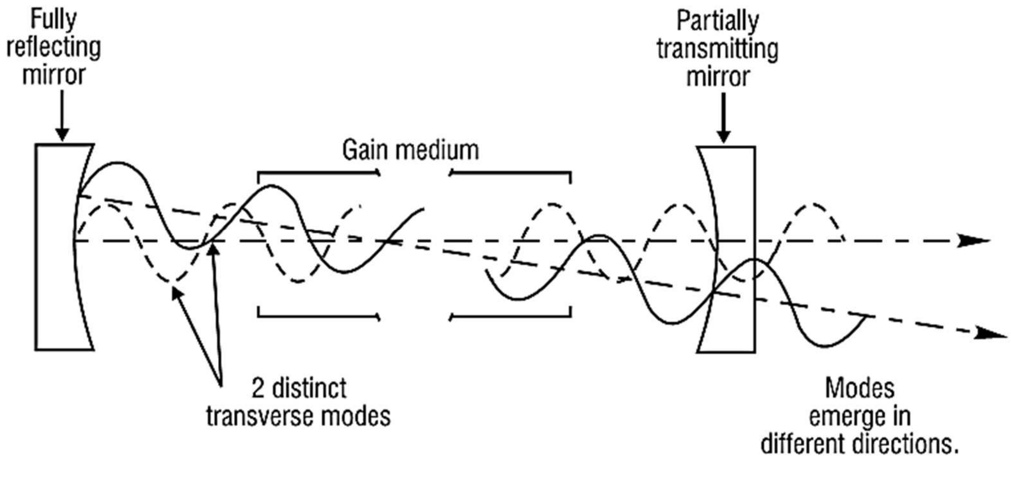


Figure 4.12 – Two transverse modes occurring simultaneously within a laser cavity. The on-axis mode is the TEM_{00} mode.

The TEM_{00} mode has a beam-intensity profile in the direction transverse to the direction of propagation that is described by a Gaussian function, and given as:

$$I = I_0 e^{-\frac{2r^2}{w^2}}, \tag{4.2}$$

where I_0 is the intensity on the beam axis at any location, r is the perpendicular distance from the beam axis, and w is defined as the beam waist. The beam waist, varying along the axis of the laser, is defined such that the intensity has fallen to $1/e^2$ of the intensity on axis. It turns out, that 86.5% of the energy is contained within the beam radius, in which $r = w$. The TEM_{00} mode is often the desired mode, because it propagates with the least beam divergence and can be focused to the tightest spot. It can generally be obtained by placing an adjustable aperture within the laser cavity and decreasing the aperture diameter until only the TEM_{00} mode remains.

4.11.4 Laser properties related to applications

Collimation. Collimated light is light in which all the light rays or waves are traveling in a specific direction, and hence they are all parallel to each other. Lasers produce the most collimated light of any type of light source. Such collimated light is used for reference beams in construction, leveling and grading land, alignment of pipe, such as sewer pipe, sending light over long distances without suffering significant divergence, and in laser pointers [11].

Monochromaticity shows how pure in color (frequency or wavelength) the laser beam is, i.e. how narrow the laser beam frequency bandwidth is.

Coherence refers to a number of various portions of a single laser beam in a step or a phase. The closeness in phase of various portions of laser frequency bandwidth is referred to as temporal or longitudinal coherence. The closeness in phase of different spatial portions of the beam after the beam has propagated a certain distance is referred to as spatial or transverse coherence.

For longitudinal or temporal coherence, the coherence length l_c is related to the wavelength λ and the total frequency bandwidth of the laser $\Delta\nu_L$ by

$$l_c = \frac{\lambda^2}{\Delta\lambda}.$$

Note: Δλ is the actual bandwidth of the laser beam given in wavelength units. For transverse or spatial coherence, the transverse coherence length l_t is related to the laser wavelength λ, the laser source diameter at its origin s, and the distance r the beam has propagated from its origin, by the following relationship:

$$l_c = \frac{r\lambda}{s}.$$

Intensity and Radiance

Intensity or irradiance is the power of the laser beam divided by the cross-sectional area of the beam. It is thus typically given in watts per square centimeter (W/cm^2). It measures the amount of energy that can be applied to a specific region within a given amount of time. It is one of the two most important parameters in using the laser for material processing such as welding, cutting, heat treating, ablating, and drilling, or for laser surgery. The other important parameter is laser wavelength, since the amount of absorption of all materials, including biological materials, is dependent upon light wavelength [11].

Radiance becomes useful when a beam propagates over a reasonable distance before it is used, or where the divergence can affect the focusing ability of the beam. Since most applications do not involve the tightest focusing possible for a given beam, intensity is usually the most important parameter.

Focusability

Many laser applications involve their ability to be focused on a very small spot size. Perhaps one of the most demanding applications is focusing the small diode laser in a compact disk player. To store as much information as possible on each disk, that information must be included in the smallest grooves possible on the disk. Hence, the diameter of the spot size, to which the laser beam can be focused, becomes a very important parameter.

The smallest diameter can be obtained with a focused laser, assuming that a single TEM_{00} mode can be from the laser; is approximately the dimension of the laser wavelength and is expressed as

$$d_{\min} \cong \frac{4\lambda(f/d)}{\pi},$$

in which the *f/d* is the focal length of the lens used for the focusing divided by the useful diameter of the lens, the same notation as on camera lenses. If the laser beam is less than the actual lens diameter, the beam diameter is used instead of the lens diameter in determining the *f/d*.

4.11.5 Semiconductor Lasers

Semiconductor lasers are small, very efficient lasers with dimensions of less than a millimeter (see semiconductor gain media). The wavelengths of commercial lasers range from approximately 600 nm in the red to 1.6 μm in the near infrared. Lasers in the blue and green are also under advanced development, but very few are available commercially. These lasers consist of small semiconductor crystals grown as such, that they can be cleaved in short segments of approximately 0.5 mm in length. The cleaving is done in a direction perpendicular to the laser axis, leaving a surface (facet) at each end of the gain medium that serves as a mirror. No reflective coatings are generally required; the cleaved surface itself serves to provide reflectivity of 35% or more from each of the two mirror surfaces, which is ample due to the very high gain or amplification present in the laser. Because of short separation between mirrors, it is generally possible to obtain laser operation on only one longitudinal mode. Also, because of the short cavity length, the laser operates in a highly multi-transverse-mode output with a high angular divergence beam. To obtain single TEM_{00}-mode operation, it is necessary to coat the two end facets of the laser with an antireflection coating at laser wavelength. Then an external mirror cavity can be installed with the appropriate mirror radii and reflectivity, as well as suitable aperture on axis to restrict beam spread [11].

Semiconductor or diode lasers, consist of a p-n junction formed in a semiconductor crystal, such as GaAs or InP, in which the p-type material has excess of holes (vacancies due to missing electrons) and the n-type material has excess of electrons. When these two types of materials are brought together to form a junction, and an electric field in the form of voltage is applied across the junction in the appropriate direction, the electrons and holes are brought together and recombine to produce recombination radiation at or near wavelength associated with the bandgap energy of the material. The population of electrons and holes within the junction provides the upper-laser-level population, and the recombination radiation spectrum is the gain bandwidth $\Delta\nu$ of the laser, typically of the 0.5 to 1.0 nm order.

Heterostructure semiconductor lasers include additional layers of different materials with similar electronic configurations, such as aluminum, indium, and phosphorous, grown adjacent to the junction to help confine the electron current to the junction region to minimize current and heat dissipation requirements (see Fig. 4.13). The laser mode in the transverse direction is either controlled by gain guiding, in which the gain is produced over a specific narrow lateral extent determined by fabrication techniques, or by index guiding, in which the index of refraction in the transverse direction is varied to provide total internal reflection of a guided mode. Quantum well lasers have smaller gain region (cross section), which confines the excitation current and thus the laser mode to an even smaller lateral region, thereby significantly reducing the threshold current and also heat dissipation requirements. Because of these low threshold requirements, quantum-well semiconductor lasers are used almost exclusively for most semiconductor laser applications.

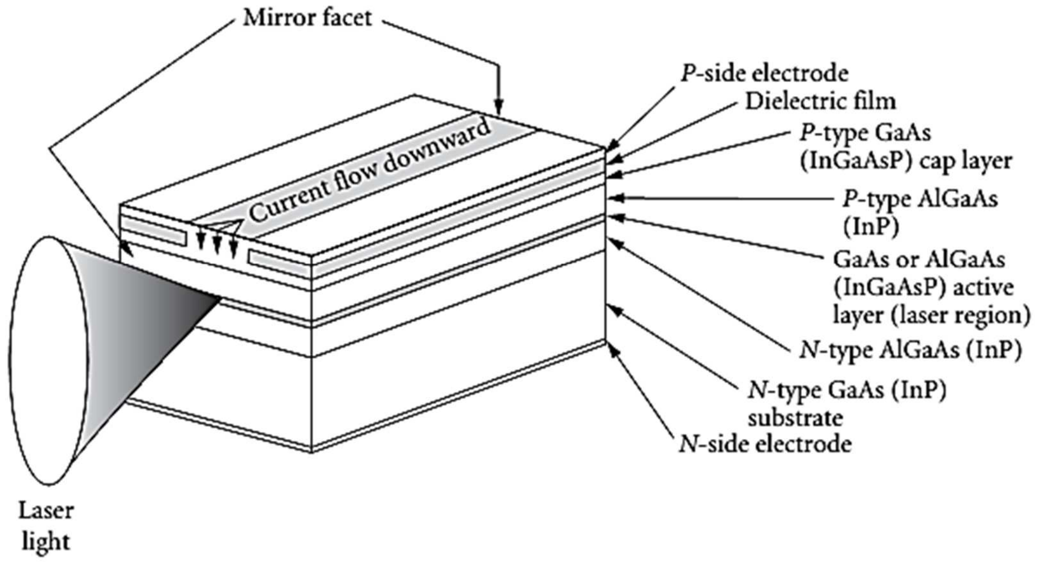


Figure4.13 – A typical heterostructure semiconductor laser showing various layers of differential materials and the narrow region, where current flows to produce the gain region in the active layer [1]

Semiconductor lasers operate over wavelengths ranging from 400 nm to 2.2 μm by using special doping materials to get the expanded or contracted bandgap energies that provide varied wavelengths. The latest additions to this class of lasers are based upon the GaN laser materials with the active region consisting of various combinations of InGaN dopings, that provide laser wavelengths in green, blue, and violet portions of the spectrum [1].

5. DETECTORS

Optical detectors convert incoming optical energy into electrical signals. Different types of optical detectors are available, covering the ultraviolet, visible, and infrared regions of the electromagnetic spectrum.

Optical detectors are used to measure optical power or energy. In laser-based fiber optic communication, a detector is employed in the receiver. In laser materials processing, a detector monitors a laser output to ensure reproducible conditions. In applications involving interferometry, detectors are used to measure position and motion of interference fringes. In most applications of light, one uses an optical detector to measure the output of a laser or other light source. Thus, good optical detectors for measuring optical power and energy are essential in most applications of photonics technology.

5.1 Types of optical detectors

Optical detectors are usually divided into two broad classes: photon detectors and thermal detectors. In photon detectors, quanta of light energy interact with electrons in the detector material and generate free electrons. To produce free electrons, the quanta must have sufficient energy to free an electron from its atomic binding forces. Wavelength response of photon detectors shows a long-wavelength cutoff. If a wavelength is longer than cutoff wavelength, the photon energy is too small to produce a free electron and response of the photon detector drops to zero.

Thermal detectors respond to the heat energy delivered by light. These detectors use some temperature-dependent effect, like a change of electrical resistance. Because thermal detectors rely on only the total amount of heat energy reaching the detector, their response is independent of wavelength.

The output of photon detectors and thermal detectors, as a function of wavelength, is shown schematically in Fig. 5.1. This figure shows typical spectral dependence of the output of photon detectors, which increases with increasing wavelength at wavelengths shorter than cutoff wavelength. At that point, the response drops rapidly to zero. The figure also shows how the output of thermal detectors is independent of wavelength, and extends to longer wavelengths than the response of photon detectors.

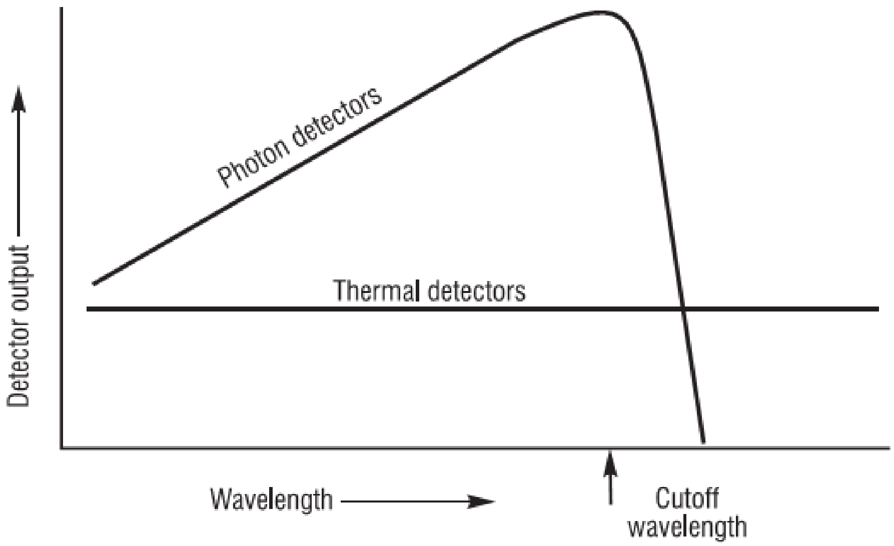


Figure5.1 – Schematic drawing of the relative output per unit input for photon detectors and thermal detectors as a function of wavelength. The position of the long-wavelength cutoff for photon detectors is indicated [11]

Photon detectors may be further subdivided according to the physical effect, that produces the detector response. Some important classes of photon detectors are listed below [11].

• **Photoconductive**. The incoming light produces free electrons which can carry electrical current so that the electrical conductivity of the detector material changes as a function of intensity of incident light. Photoconductive detectors are fabricated from semiconductor materials such as silicon.

• **Photovoltaic**. Such a detector contains a junction in a semiconductor material between a region, where the conductivity is due to electrons, and a region, where the conductivity is due to holes (a so-called pn junction). A voltage is generated when optical energy strikes the device.

• **Photoemissive**. These detectors are based on the photoelectric effect, in which incident photons release electrons from the surface of the detector material. The free electrons are then collected in an external circuit.

According to the spectral responsivity width, there are selective detectors, that are sensitive in a narrow spectrum (as photon detectors in the Fig. 5.1), and non-selective, that perceive radiation over a wide range (as thermal detectors in the same diagram). Detectors can also be divided based on the spectrum range they are sensitive to, working temperature (cooled or uncooled), purpose (measurement of weak or strong irradiant power, or power measurement of a pulse), arrangement of photosensitive elements (single detector, a line or an array) [12].

5.2 Detector characteristics

Performance of optical detectors is commonly characterized by different parameters, that are sometimes called *figures of merit*. It is important to define these parameters, because manufacturers usually describe the performance of their detectors in these terms.

5.2.1 Voltage and current of a detector

When a detector is powered by a power source with output voltage U_p, and light does not come onto the detector, dark current I_{dark} and a corresponding voltage U_{dark} appear at the output of the detector. The detector being exposed to the constant optical radiation defined by a radiometric unit like Φ_e, Φ_v, E_e or E_v, total current I_{tot} and total voltage U_{tot} are composed of dark current or voltage and photocurrent I_{ph} or voltage U_{ph}:

$$I_{ph} = I_{tot} - I_{dark}, \; U_{ph} = U_{tot} - U_{dark}.$$

The structure of total detector current is shown in Fig. 5.2. Photocurrent I_{ph} can be composed of photocurrent due to radiation from the signal source (I_{sign}) and background radiation (I_{bckgr}). Photocurrent of the signal I_{sign} can contain either alternate (I_{AC}) or direct (I_{DC}) components.

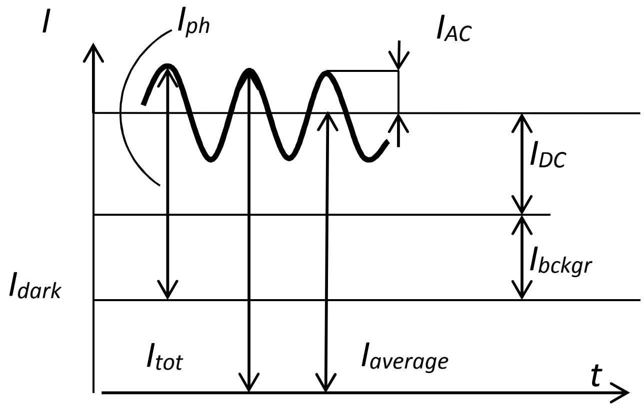


Figure5.2 — Structure of the total detector current

5.2.2 Responsivity

Responsivity is the *detector output per unit of input power*. Units of responsivity are either amperes/watt or volts/watt, depending on whether the output is electric current or voltage. [11]

Responsivity is defined as a relation of constant input and output quantities

$$S_{x,y} = x / y, \tag{5.1}$$

where *x* is an electric quantity, *y* is a radiometric quantity. For example:

$S_{I,\Phi e} = I/\Phi_e$, [A/W] is *current responsivity* to the radiant power,

$S_{U,\Phi e} = U/\Phi_e$, [V/W]is *voltage responsivity* to the radiant power,

$S_{I,\Phi v} = U/\Phi_v$, [A/lm] is voltage responsivity to the flux,

$S_{I,Ev} = I/E_v$, [A/lux] is current responsivity to the illuminance, etc.

Responsivity to a differential input quantity, that is also referred to as *sensitivity*, is expressed as a relation of delta quantities:

$$S_{x,y} = \Delta x / \Delta y.$$

For example, $S = \Delta I / \Delta \Phi_e$ shows how much the current (ΔI) changes, if the incident radiant power changes at $\Delta \Phi_e$.

Responsivity is an important parameter that is usually specified by a manufacturer. A responsivity value allows the user to determine how much electric signal is available on a detector for a specific application.

5.2.3 Spectral response

The spectral response defines how the performance of a detector (responsivity or detectivity) varies with wavelength. Spectral response presents generalized curves showing relative spectral response, as a function of wavelength for photon detectors and thermal detectors. The exact shape of spectral response and numerical values depend on the detector type and the material, from which the detector is fabricated. Again, a manufacturer usually specifies a spectral response curve. A detector that responds well in the spectral region of importance for a specific application should be chosen. The spectral response is defined as

$$S_{\lambda,I,\Phi} = \frac{dI}{d\Phi_{\lambda e}}.$$

Responsivity to the whole spectrum is called *total response*, and to a specific wavelength is called *spectral response*. They are related with the expression

$$S_{tot,I,\Phi} = \frac{I_e}{\Phi} = \frac{\int_0^\infty S_\lambda \cdot \Phi_\lambda(\lambda) d\lambda}{\int_0^\infty \Phi_\lambda(\lambda) d\lambda} = S_{\lambda \max} \kappa, \qquad (5.2)$$

$$d\Phi_\lambda = \Phi_\lambda \cdot d\lambda,$$

where κ is detector efficiency [12].

Total responsivity depends on spectral response $S_\lambda(\lambda)$ of a detector and spectral radiant power of a radiation source $\Phi_\lambda(\lambda)$.

Usually, there is a load in a circuit of a detector, and the voltage on the load due to the signal is expressed as

$$U_{sign} = I_{sign} \cdot R = \int_0^\infty S_{\lambda,v} \cdot \Phi_\lambda(\lambda) d\lambda = R \cdot \int_0^\infty \Phi_\lambda(\lambda) \cdot S_{\lambda I} d\lambda .$$

Thus, this expression relates voltage and current responsivity of a detector:

$$S_v = \frac{U_{sign}}{\Phi_v} = I \cdot R / \Phi_v = R \cdot S_I .$$

Usually a detector's datasheet contains total responsivity measured with calibration radiation source, relative spectral response $S_{rel}(\lambda) = S_{abs}(\lambda) / S_{\lambda \max}$, voltage and load resistance, that were used while defining the responsivity.

5.2.4 Noise equivalent power

Noise equivalent power is a figure of merit, which depends on noise characteristics. This is an optical power, that produces a signal voltage (current) equal to a noise voltage (current) of a detector in a specified bandwidth. It is defined as

$$\Phi_{\min} = \frac{\sqrt{\overline{U}_N^2}}{S_U}, \ \Phi_{\min} = \frac{\sqrt{\overline{I}_N^2}}{S_I} .$$

But the figure of merit, that is more commonly used, is the *unit frequency bandwidth noise equivalent power* (NEP, it is also often referred to as simply *noise equivalent power*, usually instead of $\Phi_{\min}$, or *spectral noise equivalent power* [1]). This is the RMS value of sinusoidally modulated monochromatic radiant power incident upon a detector, which gives rise to an RMS signal voltage equal to the RMS noise voltage from the detector in a 1-Hz bandwidth.

In other words, this is the optical power that produces a signal voltage (or current) equal to the noise voltage (or current) of the detector, referenced to a 1-Hz bandwidth, since the noise is dependent on the bandwidth of the measurement, that is why the bandwidth must be specified. The equation, defining the NEP, is

$$\mathrm{NEP} = \Phi_{\min} \Big/ \sqrt{\Delta f}\ ,$$

where Δf is the measurement bandwidth. The NEP has units of watts/(Hz)$^{1/2}$, usually called "watts per root hertz." From the definition, it is apparent that the lower the value of the NEP, the better are the characteristics of the detector for detecting a small signal in the presence of noise.

The NEP of the detector is dependent on the area of the detector. To provide a figure of merit, that is dependent on the intrinsic properties of the detector, not on how large it happens to be, a term called *specific noise equivalent power* (NEP*) is defined. This is the NEP referenced to a unit area of the detector:

$$\mathrm{NEP}^* = \Phi_{\min} \Big/ \sqrt{A \cdot \Delta f}\ ,$$

where A is the detector area.

5.2.5 Detectivity

Detectivity is the inverse of NEP. When comparing detectors, it is also common to compare *normalized detectivity*. Normalized detectivity is represented by the symbol D*[D-star]. It is defined as the square root of the detector area per unit value of the NEP.

$$D^* = A^{1/2}/\mathrm{NEP} = 1/\mathrm{NEP}^*.$$

Since many detectors have the NEP proportional to the square root of their areas, $D^*$is independent of the area of the detector. The detectivity thus gives a measure of the intrinsic quality of the detector material itself.

When a value of D^* for an optical detector is measured, it is usually measured in a system in which the incident light is modulated or chopped at a frequency f, so as to produce an AC signal, which is then amplified with an amplification bandwidth Δf. These quantities must also be specified. Dependence of D^*on wavelength λ, frequency f, at which the measurement is made, and the bandwidth Δf is expressed by the notation $D^*(\lambda, f, D_f)$. The reference bandwidth is often 1 Hertz. The units of $D^*(\lambda, f, D_f)$ are (cm-Hz)$^{1/2}$/watt. A high value of $D^*(\lambda, f, D_f)$ means that the detector is suitable for detecting weak signals in the presence of noise. The effect of modulation frequency and bandwidth on the noise characteristics is described in Section 5.4.

5.2.6 Quantum efficiency

Another common figure of merit for optical detectors is quantum efficiency. Quantum efficiency is defined as the ratio of countable events produced by photons incident on a detector to the number of incident photons. If the detector is a photoemissive detector, that emits free electrons from its surface when light strikes it, the quantum efficiency is the number of free electrons divided by the number of incident photons. If the detector is a semiconductor pn-junction device, in which hole-electron pairs are produced, the quantum efficiency is the number of hole-electron pairs divided by the number of incident photons. If, over a period of time, 100,000 photons are incident on the detector and 10,000 hole-electron pairs are produced, the quantum efficiency is 10%.

Quantum efficiency is basically another way of expressing effectiveness of incident optical energy for producing an output of electrical current. Quantum efficiency Q (in percent) may be related to responsivity by the relation: $Q = 100 \times S_\lambda \times (1.2395/\lambda)$, where S_λ is responsivity (in amperes per watt) of the detector at wavelength λ (in micrometers).

5.2.7 Detector response time

Another useful detector characteristic is speed of the detector response to changes in light intensity. If a light source is instantaneously turned on and irradiates an optical detector, it takes a finite time for current to appear at the output of the device and to reach a steady value. If the source is turned off instantaneously, it takes a finite time for the current to decay back to zero. The term *response time* refers to the time it takes detector current to rise to a value equal to 63.2% of the steady-state value which is reached after a relatively long period of time (this value is numerically equal to $1 - 1/e$, where e is the base of the natural logarithm system). *Recovery time* is the time it takes for photocurrent to fall to 36.8% of the steady-state value, when light is turned off instantaneously [11].

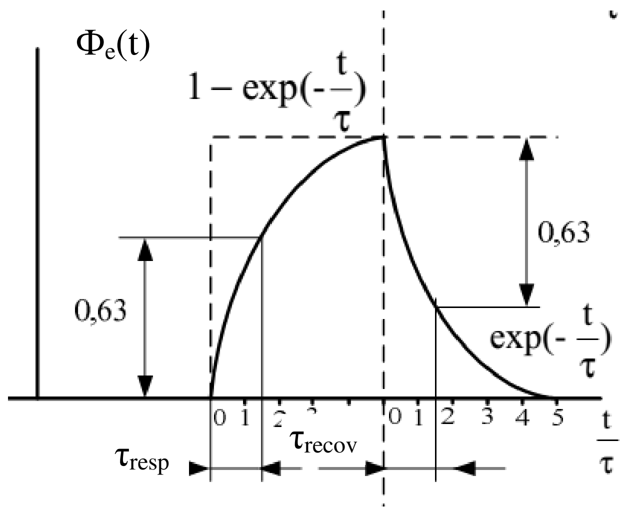


Figure 5.3 – Detector response and recovery times

As optical detectors are often used for detection of fast pulses, another important term, *rise time*, is often used to describe the speed of the detector response. Rise time is defined as the time difference between the point, at which the detector has reached 10% of its peak output, and the point, at which it has reached 90% of its peak response, when it is irradiated by a very short pulse of light. *Fall time* (also called *decay time*) is defined as the time between the 90% point and the 10% point on the trailing edge of the pulse waveform (Fig. 5.4). It should be noted that fall time may differ numerically from rise time.

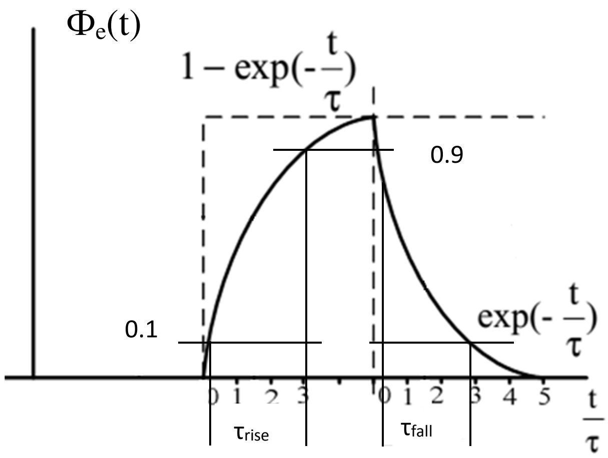


Figure 5.4 – Detector rise and fall times

Of course, light sources are not turned on/off instantaneously. To make accurate measurements of rise time and fall time, the source used for the measurement should have a rise time much less than the rise time of the detector being tested. Generally, a source, whose rise time is less than 10% of rise time of the detector being tested, should be used.

Intrinsic response time of an optical detector arises from transit time of photogenerated charge carriers within the detector material and from the inherent capacitance and resistance associated with the device. The measured value of response time is also affected by the value of load resistance, that is used with the detector, and may be longer than inherent response time. There is a tradeoff in the selection of load resistance between speed of response and high sensitivity. It is not possible to achieve both simultaneously. Fast response requires a low load resistance (generally 50 ohms or less), whereas high sensitivity requires a high value of load resistance. It is also important to keep any capacitance associated with the circuitry, electrical cables, and display devices as low as possible. This will help keep the RC (resistance × capacitance) time constant low. Manufacturers often quote nominal values for rise times of their detectors. These should be interpreted as minimum values, which may be achieved only with careful circuit design and avoidance of excess capacitance and resistance in the circuitry.

5.2.8 Linearity

Another important characteristic of optical detectors is their linearity. Detectors are characterized by a response in which the output is linear with incident intensity. The response may be linear over a broad range, perhaps many orders of magnitude. If the output of the detector is plotted versus the input power, there should be no change in the slope of the curve. Noise will determine the lowest level of incident light that is detectable. The upper limit of the input/output linearity is determined by the maximum current that the detector can produce without becoming saturated. Saturation is a condition in which there is no further increase in detector response as the input light intensity is increased. When the detector becomes saturated, one can no longer rely on its output to represent the input faithfully. The user should ensure that the detector is operating in the range in which it is linear (Fig. 5.5).

Manufacturers of optical detectors often specify maximum allowable continuous *light level.* Light levels in excess of this maximum may cause saturation, hysteresis effects, and irreversible damage to the detectors. If light occurs in the form of a very short pulse, it may be possible to exceed the continuous rating by some factor (perhaps as much as 10 times) without damage or noticeable changes in linearity.

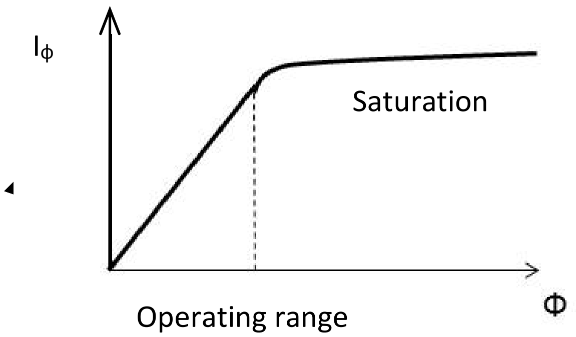


Figure 5.5 – Detector operating range

Detector is used at linear growing part, the section with constant current is a saturation part of the characteristic.

5.3 Conversion of detector parameters

Total responsivity and noise equivalent power are defined with reference to a calibration source. In real conditions the spectrum of a light source used with a detector usually differs from the calibration source, as well as operation conditions, such as spectral transmission, temperature, etc. That is why selective detectors characteristics, such as total responsivity and NEP, need to be converted for a specific light source.

A current generated by a detector is expressed as $I = S_v \Phi_v$, where S_v is total responsivity of the detector in photometric units (amps/lumen), and Φ_v is luminous flux. On the other hand, the detector generates the same current, if the responsivity and flux are given in radiometric units (ampere/watt and watt respectively): $I = S_e \Phi_e$.

Luminous flux Φ_v relates to radiant power Φ_e, according to the expressions (2.20) and (2.23), discussed in Section 2.3.2, as follows:

$$\Phi_v = \Phi_e \cdot K_{\max} \cdot \kappa_{eye}, \tag{5.3}$$

where K_{max}=683 lm/W is the maximum spectral luminous efficacy (see Section 2.3.1), κ_{eye} is the efficacy of a source for the eye (2.22). Thus, two kinds of responsivity are related by the expression $S_v \Phi_v = S_e \Phi_e = S_e K_{\max} \kappa_{eye}$, i.e.

$$S_e = S_v K_{\max} \kappa_{eye}. \tag{5.4}$$

Spectral response is converted similarly:

$$S_{e\lambda} = S_{v\lambda} K_{\max} V(\lambda),$$

where $V(\lambda)$ is relative spectral luminous efficacy (Section 2.3.2: Eq. (2.18), (2.19)).

NEP is converted in a way similar to (5.3):

$$\mathrm{NEP}_v = \mathrm{NEP}_e \cdot K_{\max} \cdot \kappa_{eye};$$

and detectivity similar to (5.4):

$$D_e = D_v K_{\max} \kappa_{eye},$$

as it is reverse to NEP.

This conversion can be used if the light source remains the same and we only need to convert its characteristic from photometric units to radiometric ones, or otherwise. If another light source with a spectrum different from the calibration light source is used, the conversion is made as follows.

Let the calibration source be denoted with the superscript *I* and the working light source with the superscript *II*. According to (5.2), the total responsivity to the calibration radiation source can be stated as $S_{tot}^{I} = S_{\lambda\max} \kappa^{I}$, and the responsivity to the working radiation source as $S_{tot}^{II} = S_{\lambda\max} \kappa^{II}$, as soon as efficiency κ for the two sources is different. As $S_{\lambda\max}$ remains the same for the detector, total responsivity is put as follows:

$$S_{tot}^{II} = S_{tot}^{I} \kappa^{II} / \kappa^{I} .$$

Note that this conversion can be made only if $S_e^{I,II}$ are stated in terms of radiometric quantities (it is indicated by the subscript e). Similarly, total NEP and detectivity are converted as follows:

$$NEP_e^{II} = NEP_e^{I} \kappa^{I} / \kappa^{II} ,$$

$$D_e^{II} = D_e^{I} \kappa^{II} / \kappa^{I} .$$

5.4 Noise sources

Noise in optical detectors is a complex subject. Noise is defined as any undesired signal. It masks the signal that is to be detected.

Noise can be external and internal. External noise involves disturbances that appear in the detection system because of the factors outside the system. Internal noise includes all noise generated within the detection system itself. Every electronic device has internal sources of noise, which represent an ever-present limit to the smallest signal that may be detected by the system.

Noise cannot be described in the same manner as usual electric currents or voltages. Currents or voltages are functions of time, such as constant direct currents or sine-wave alternating voltages. The noise output of an electrical circuit as a function of time is completely erratic, and the output, which will be at any instant, cannot be predicted. In other words, there will be no indication of regularity in the waveform. The output is random.

Five noise sources typical for optical detectors are described further.

5.4.1 Photon noise

This is the noise that appears because of the random arrival rate of photons in the light being measured and from the background. This noise source is external to a detector. It imposes the ultimate fundamental limit to the detectivity of a photodetector.

The photon noise associated with fluctuations in the arrival rate of photons in the desired signal is not something that can be reduced, while the contribution of fluctuations in the arrival of photons from the background, a contribution called background noise, can be reduced.

The background noise increases with the field of view of the detector and with the temperature of the background. In some cases, it is possible to reduce the field of view of the detector to view only the source of interest. In other cases, it is possible to cool the background. Both measures may be used to reduce the background noise contribution to photon noise.

The types of noise described here, or a combination of them, will set an upper limit to the detectivity of an optical detector system.

Photon dispersion in a portion of background radiation is put as

$$\Delta\bar{\Phi}_{bgr}^2 = 8\alpha_T \varepsilon_{Tbgr} k T_{bgr}^5 \sigma A \Delta f \,,$$

where α_T=ε_{Td} is absorption of the detector, ε_{Tbgr} is the background emissivity, T_{bgr} is the background temperature, σ is Stefan-Boltzmann's constant, A is the area of the detector, Δf is the frequency bandwidth. The fluctuation of radiation emitted by the detector itself is defined as

$$\Delta\bar{\Phi}_d^2 = 8k\sigma A \varepsilon_{Td} T_d^5 \Delta f \,,$$

where ε_{Td} is the emissivity of the detector, T_d is the temperature of the detector.

5.4.2 Thermal (Johnson, Nyquist) noise

Thermal noise, or *Johnson, or Nyquist noise,* is generated by thermal fluctuations in conducting materials. It results from the random motion of electrons in a conductor. The electrons are in constant motion, colliding with each other and with the atoms of the material.

Each motion of an electron between collisions represents a tiny current. The sum of all these currents taken over a long period of time is zero, but their random fluctuations over short intervals constitute Johnson noise.

$$\bar{I}_J^2 = \frac{4 \cdot k \cdot T}{R} \cdot \Delta f \,,\ \bar{U}_J^2 = 4 \cdot k \cdot T \cdot R \cdot \Delta f \,,$$

where T is temperature, Δf is frequency bandwidth, R is resistivity, k is Stefan-Boltzmann's constant, k=1.38·10^{-23} J/K.

To reduce the magnitude of Johnson noise, one may cool the system, especially the load resistor. The value of the load resistance should be reduced, although this is done at the price of reducing the available signal. The bandwidth of the amplification should be kept small; one Hz is a commonly employed value.

This noise is white, i.e. its spectral density is constant over all frequencies.

5.4.3 Shot noise

The term *shot noise* is derived from fluctuations in the stream of electrons in a vacuum tube. These variations create noise because of the random fluctuations in the arrival of electrons at the anode. The shot noise name arises from the similarity to the noise of a hail of shots striking a target.

In semiconductors, the major source of shot noise is random variations in the rate at which charge carriers are generated and recombine. This noise, called *generation-recombination* or *gr noise*, is the semiconductor analogue of shot noise. It is defined by the formula

$$\bar{I}^2_{\text{shot}} = 2eI_{dc}\Delta f \ ,$$

where e is the electron charge, I_{dc} is the detector average current, Δf is frequency bandwidth. The shot noise voltage is

$$\bar{U}^2_{\text{shot}} = 2eI_{dc}R_l^2\Delta f \ ,$$

where R_l is the load resistance.

For the photomultiplier (see Section 6.4.1) it is

$$\bar{I}^2_{\text{shot}} = 2eI_{ctd}M^2(1+B)\Delta f \ ,$$

where I_{ctd} is the cathode current, B is the shot noise ratio (depends on the photomultiplier type), M is the multiplication ratio.

For the intrinsic transition-based avalanche photodiode the shot noise current is expressed as

$$\bar{I}^2_{shot} = 2eI_{dc}M^3\Delta f \ ,$$

where M is the multiplication ratio.

Shot noise may be minimized by keeping any DC component to the current small, especially the dark current, and by keeping the bandwidth of the amplification system small. This noise is also white.

Generation-recombination noise can be considered as the shot noise for photovoltaic detectors.

5.4.4 Generation-recombination noise

This noise is a kind of shot noise described above and is applicable to semiconductor detectors. Charge carriers are generated both by (optical) photons and (thermal) phonons. Fluctuations in these generation rates cause noise; fluctuations in carrier recombination times cause recombination noise. With photovoltaic pn-junctions, carriers are swept away before recombination, so that recombination noise is absent. This noise is defined by

$$\bar{U}_{g-r}^2 = 4U_p^2 \cdot \frac{R_l^2 R_{dark}^2}{\left(R_l + R_{dark}\right)^2} \cdot \frac{\tau \Delta f}{n \cdot v} \cdot \frac{1}{1 + \left(2\pi f \tau\right)^2},$$

where U_p is the power voltage, R_{dark} is the dark resistance, R_l is the load resistance, τ is lifetime of free carriers, n is carriers' concentration, 1/cm^3, v is photogeneration location volume, cm^3, and the product of $n{\cdot}v$ denotes carriers' number in the conduction band, f is the modulation frequency, Δf is the frequency bandwidth [12].

5.4.5 Modulation (1/f) noise

The term *modulation (1/f) noise* (pronounced *one over f*) is used to describe several noise types that are present when the modulation frequency *f* is low. This type of noise is also called *excess noise* because it exceeds shot noise at frequencies below a few hundred Hertz [11].

The mechanisms that produce 1/*f* noise are poorly understood. The noise power is inversely proportional to *f*, the modulation frequency. This dependence of the noise power on modulation frequency leads to the name for this type of noise.

To reduce 1/*f* noise, an optical detector should be operated at a reasonably high frequency, often as high as 1000 Hz. This value is high enough to reduce the contribution of 1/*f* noise to a small amount. It is expressed as

$$\bar{U}_{1/f}^2 = \left(\frac{B I_{dc}^2 R_d^2}{f}\right) \Delta f \ ,$$

where B is the ratio, that depends on the photodetector type, R_d is the detector resistance, I_{dc} is the average current in the detector circuit, Δf is frequency bandwidth.

This type of noise is prominent in thermal detectors and may dominate the low-frequency noise (in this case it is called *flicker noise*) characteristics of photoconductive and photovoltaic quantum detectors, as well as other electronic devices, such as transistors and resistors [1].

$$I_{flkr}^2 = 2eI_{dc}\left(1 + \frac{BI_{dc}}{Af}\right)\Delta f \ ,$$

where e is the electron charge, I_{dc} is the average current in the detector circuit, D is the ratio that depends on the photodetector type, A is the photocathode area.

The total radiation fluctuation is thus expressed as

$$\Delta\bar{\Phi}^2_{phn} = \Delta\bar{\Phi}^2_{bgr} + \Delta\bar{\Phi}^2_{d} = 8k\sigma A\alpha_T \Delta f\left(\varepsilon_{Tbgr}T^5_{bgr} + T^5_d\right),$$

so, resulting voltage fluctuation due to the photon noise is defined as

$$\bar{U}^2_{phn} = S^2_{bgr}\Delta\bar{\Phi}^2_{bgr} + S^2_d\Delta\bar{\Phi}^2_d,$$

where S_{bgr} is detector integral responsivity to background radiation, S_d is detector integral responsivity to proper detector radiation.

The resulting noise is a sum of all noises present at a detector:

$$\bar{U}^2_{\Sigma} = \bar{U}^2_{phn} + \bar{U}^2_{therm} + \bar{U}^2_{\text{shot}} + \ldots$$

6. PHOTON DETECTORS

In photon detectors, quanta of light energy produce free electrons. The photon must have sufficient energy to exceed the threshold. In other words, the wavelength must be shorter than cutoff wavelength. Three types of photoeffects that are often used for detectors are considered. These are the photovoltaic effect, the photoemissive effect, and the photoconductive effect. The most important photodetector of each type: the photoconductor, the photodiode and the photomultiplier, are discussed further.

Photoconductors that utilize excitation of an electron from the valence to conduction band are called intrinsic detectors. Those, which operate by exciting electrons into the conduction band or holes into the valence band from states within the band (impurity-bound states, quantum wells, or quantum dots), are called extrinsic detectors (Fig. 6.1).

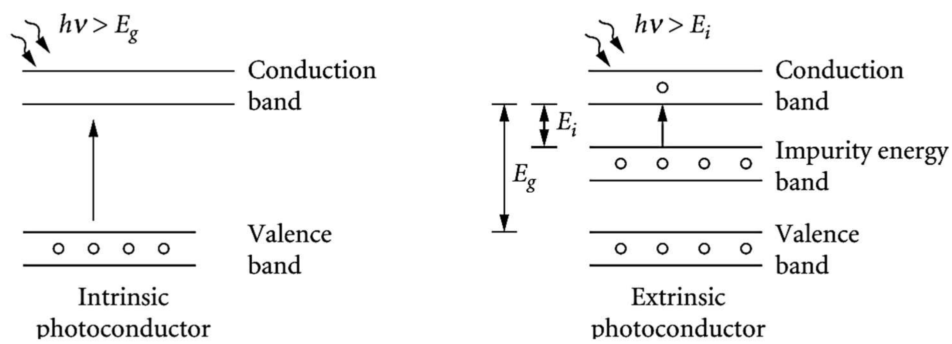


Figure 6.1 – Functional diagram of an intrinsic and extrinsic photodetector [1]

Intrinsic detectors excite electrons between the valence and conduction band. Extrinsic detectors excite electrons (or holes) from states within the band to the conduction (valence) band.

Cutoff wavelength for the intrinsic photoeffect is defined as $\lambda = h \cdot c / \Delta E_{gap}$, here ΔE_{gap} is the energy gap between the valence and conduction band. For the donor (n-type) or acceptor (p-type) semiconductor cutoff wavelength depends on the respective energy gap for the donor or the acceptor impurity level: $\lambda = h \cdot c / \Delta E_d$, $\lambda = h \cdot c / \Delta E_a$. For the photoemissive effect, cutoff wavelength is related to the work function A_{ph} of the cathode: $\lambda = h \cdot c / A_{ph}$.

6.1 Photoconductive Detectors

The first phenomenon used in optical detectors is photoconductivity. A semiconductor in thermal equilibrium contains free electrons and holes. The concentration of electrons and holes is changed if light is absorbed by the semiconductor. The light must have photon energy large enough to produce free electrons within the material. The increased number of charge carriers leads to an increase in the electrical conductivity of the semiconductor. The device is used in a circuit with a bias voltage and a load resistor in series with it. The change in electrical conductivity leads to an increase in the current flowing in the circuit, and hence to a measurable change in the voltage drop across the load resistor.

The typical structure of a photoconductor and its circuit are shown in Fig. 6.2.

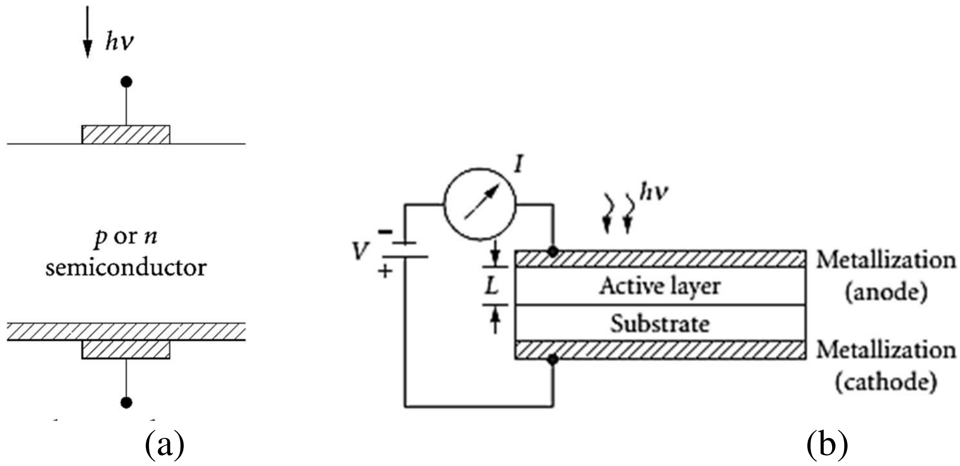


Figure 6.2 — Photoconductor structure (a) and circuit (b)

Photoconductive detectors are most widely used in the infrared region, at wavelengths, where photoemissive detectors are inoperable. Many different materials are used as infrared photoconductive detectors. The exact value of detectivity for a specific photoconductor depends on the operating temperature and on the field of view of the detector. Most infrared photoconductive detectors operate at a cryogenic temperature (frequently liquid nitrogen temperature, 77 K), which may involve some inconvenience in practical applications.

A photoconductive detector uses a crystal of semiconductor material, that has low conductance in the dark and an increased value of conductance when it is illuminated. It is commonly used in a series circuit with a battery and a load resistor. The semiconductor element has its conductance increased by light. The presence of light leads to increased current in the circuit and to increased voltage drop across the load resistor. The equivalent circuit of a photoconductor is illustrated in Fig. 6.3.

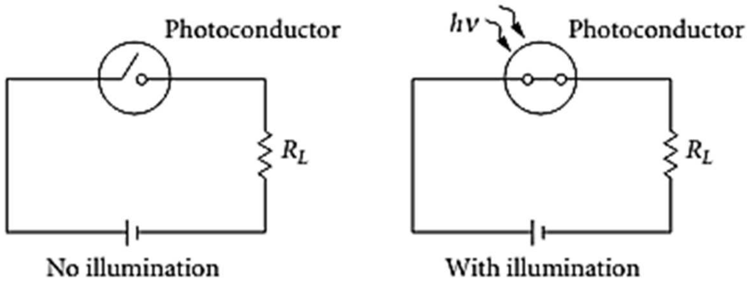


Figure 6.3 –Equivalent circuit diagram of a photoconductor

There are various circuits of photoconductors. Only typical schemes are considered here (Fig. 6.4).

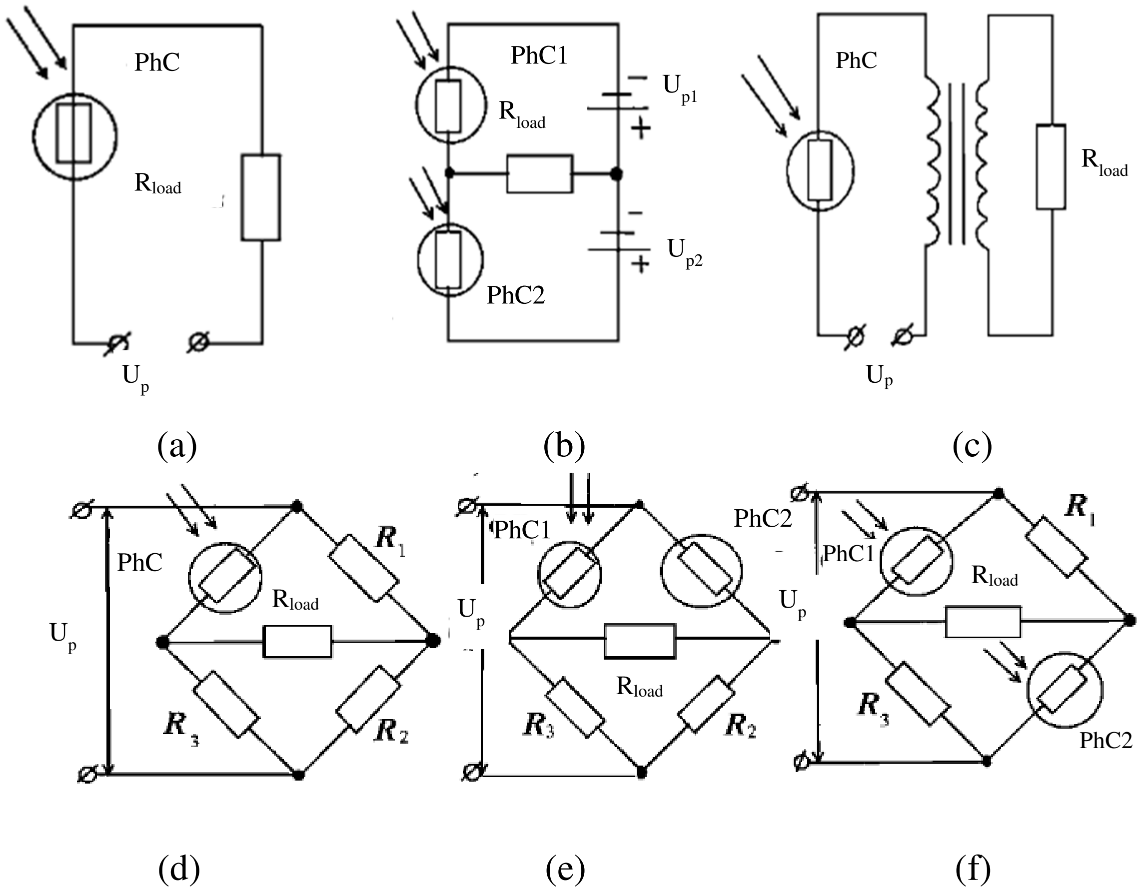


Figure 6.4 –Recommended circuits for photoconductors

The layout in Fig. 6.4 (a) presents the voltage division circuit, that allows to measure radiant power directly. If the device is not irradiated, its resistance equals to dark resistance: $R_{ph}=R_{dark}$, and dark current is $I_{dark}=U_p/\left(R_{dark}+R_{load}\right)$, where U_p is power supply voltage, and R_{load} is the resistance of the load resistor. Once the photoconductor is illuminated, current through the photoconductor changes as follows:

$$I = U_p \big/ \left(R_{dark} - \Delta R_{ph} + R_{load} \right),$$

where ΔR_{ph} is a change of resistance on the photoconductor due to illumination.

The differential circuit Fig. 6.4 (b) is used for compensation of illumination from the background, power supply being separate and constant for both circuit parts. The differential circuit can be used both for direct and comparative measurements. In this circuit currents are in counter directions, thus, when irradiation on both PhC1 and PhC2 is equal, the current at the load resistor R_{load} is zero, and not zero, if radiant power on one of the photoconductors prevails.

In the transformer circuit, Fig. 6.4 (c), the sensitivity of the photoconductor increases as all power source voltage is entirely applied to the photoconductor.

The circuit is also isolated from power source direct current, and, if changed, it does not influence on the photoconductor operation mode, and background illumination does not cause voltage drop on the load.

Bridge circuits Fig. 6.4 (d-f) are widely used for comparative and direct measurements. When photoconductors are not exposed to light, resistance of loads and photoconductors must be set in equilibrium. For circuit (d) the equilibrium condition is expressed as

$$\frac{R_{ph}}{\mathrm{R}_3} = \frac{R_1}{R_2},$$

for other circuits it is similar with corresponding terms. When the bridge circuit is in equilibrium, there is no current on R_{load}. Measurements can be made by measuring a voltage drop on R_{load}, when the photoconductor is exposed to light, or by adjusting R_2 to achieve an equilibrium (zero current on the load resistor).

6.2 Photovoltaic Detectors

The photovoltaic effect occurs at a junction in a semiconductor. The junction is a boundary between a region where the conductivity is due to electrons and a region where the conductivity is due to holes (the absence of electrons). This is called a pn junction. At the junction, an electric field is present internally, due to a change in the level of conduction and valence bands (contact voltage U_c in Fig. 6.5). This change leads to the electrical rectification effect produced by such junctions, as the pn junction enables either holes or electrons pass. The photovoltaic effect is the generation of voltage when light strikes a semiconductor pn junction [11].

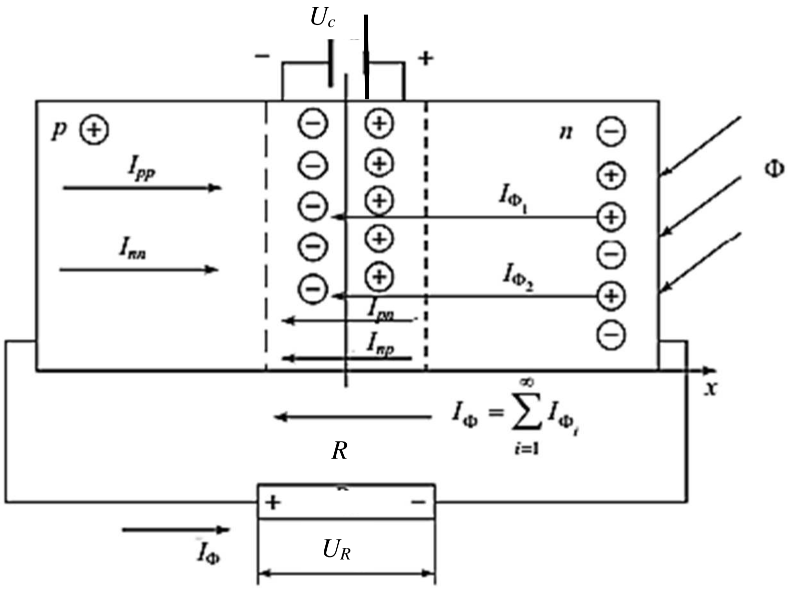


Figure 6.5 – Photovoltaic mode of photodiode operation. [12]

The first mode of photodiode operation to be considered is the *photovoltaic mode*. The photodiode being exposed at one side (here at the n-semiconductor side) generates electron-hole pairs. The electric field at the junction separates the pair and moves the electron into the n-type region and the hole into the p-type region. This leads to an open circuit voltage, that can be measured externally. For minority carriers U_c is accelerating voltage, while for majority carriers U_c is blocking voltage. Thus, both in p-type and n-type semiconductors the number of carriers, i.e. holes and electrons, increases respectively. That leads to generation of electromotive force, directed against the diffusion field of p-n junction. If connected to the load, the photocurrent I_Φ is made by minority carriers and its direction coincides with the direction of minority carrier dark current (I_Φ in Fig. 6.5, I_{nn}, I_{pp} – major carrier currents, I_{np}, I_{pn} – reverse drift current of minor carriers caused by junction potential difference). The resulting current in the circuit is expressed as

$$I = I_S \cdot \left[\exp\left(\frac{e \cdot U_R}{k \cdot T} \right) - 1 \right] - I_\Phi, \tag{6.1}$$

where $I_s = I_{np} + I_{pn}$ is the carrier dark current, U_R is load resistance, k – is Boltzmann's constant, T is the temperature, $I_\Phi$is the photocurrent ($I_\Phi = S \cdot \Phi$, S is for responsivity).

The photovoltaic effect is measured using a high-impedance voltage-measuring device, which essentially measures the open-circuit voltage produced at the junction.

The other mode of photodiode operation is the *photodiode mode*. In this case a DC power source is connected into the photodiode circuit in inverse polarity to create inverse bias in the pn-junction. It increases the resistance of pn-junction for majority carriers, their current equals to zero, and the applied voltage accelerates minority carriers, so that the photocurrent is added to the inversed current generated by the power source, in inverse direction. The total current in the circuit will be $I = I_\Phi + I_S = S\Phi + I_S$. The direction of the current is the same as for $I_\Phi$in Fig. 6.6. The voltage on the load will be calculated as $U = IR = (S\Phi + I_S)R$. Current equation for the photodiode mode is

$$I = I_S \cdot \left[\exp\left(\frac{e \cdot \left(U_R - U_p \right)}{k \cdot T} \right) - 1 \right] - I_\Phi,$$

where all designations are the same as in Eq. (6.1), and U_p is power source voltage [12].

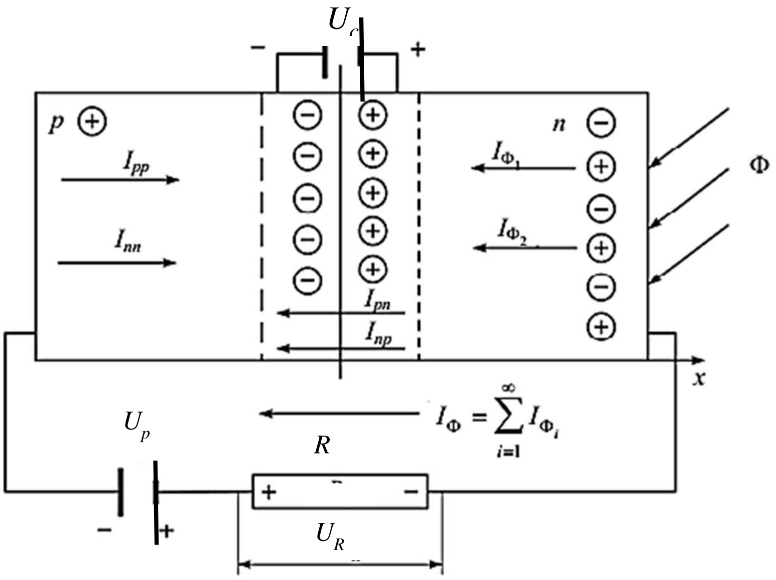


Figure 6.6 – Photodiode mode principle [12]

A variety of structures is available. No single photodiode structure can best meet all requirements. One of the most common structures, planar-fused photodiode, is shown in Fig. 6.7. This structure provides high breakdown voltage and low leakage current.

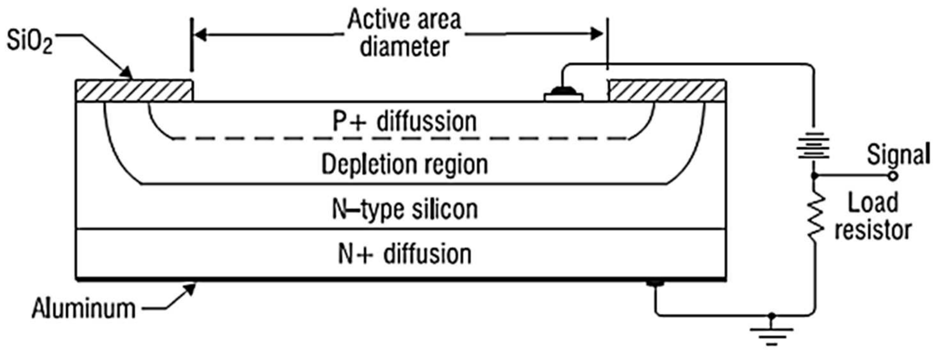


Figure 6.7 — Typical structure of a photodiode [11]

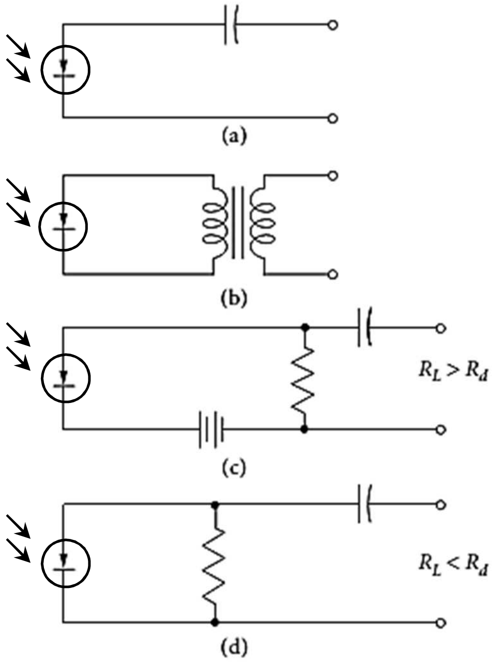


Figure 6.8 — Recommended circuits for InAs detectors: a) open circuit, b) transformer, c) reversed bias, d) fast response [1]

Recommended circuits for photodiode detectors:

Open circuit: Photovoltaic InAs detectors with areas less than 2×10^{-2} cm require no bias when operated and can be connected directly into the input stage of amplifier (capacitor ensures elimination of DC bias from amplifier) (Fig. 6.4 a).

Transformer: Useful when using InAs at zero bias, particularly at room temperature, where diode impedance is low (Fig. 6.4b).

Reversed bias: At temperatures greater than 225 K considerable gain in impedance and responsivity is achieved by reverse-biasing (Fig. 6.4c).

Fast response: To utilize the short intrinsic time constant, it is sometimes necessary to load the detector to lower the RC of the overall circuit (reverse bias will also lower detector capacitance) (Fig. 6.4d).

The current-voltage characteristics are shown in Fig. 6.9. The curve marked Φ=0 shows the current-voltage relation in the absence of light. It shows the familiar rectification characteristics of a pn semiconductor diode. The other curves represent the current-voltage characteristics, when the device is illuminated at different light levels. A photovoltaic detector, with zero applied voltage, is represented by the intersections of different curves with lines on the right from the vertical axis. A photodiode detector is operated in the lower left quadrant of this figure, where the current drawn through an external load resistor increases with increasing light level. In practice, one measures the voltage drop appearing across the load resistor. Fig.6.9 shows qualitatively how a photodiode operates. No quantitative values are shown for the axes in this figure; these values will vary depending on the material used.

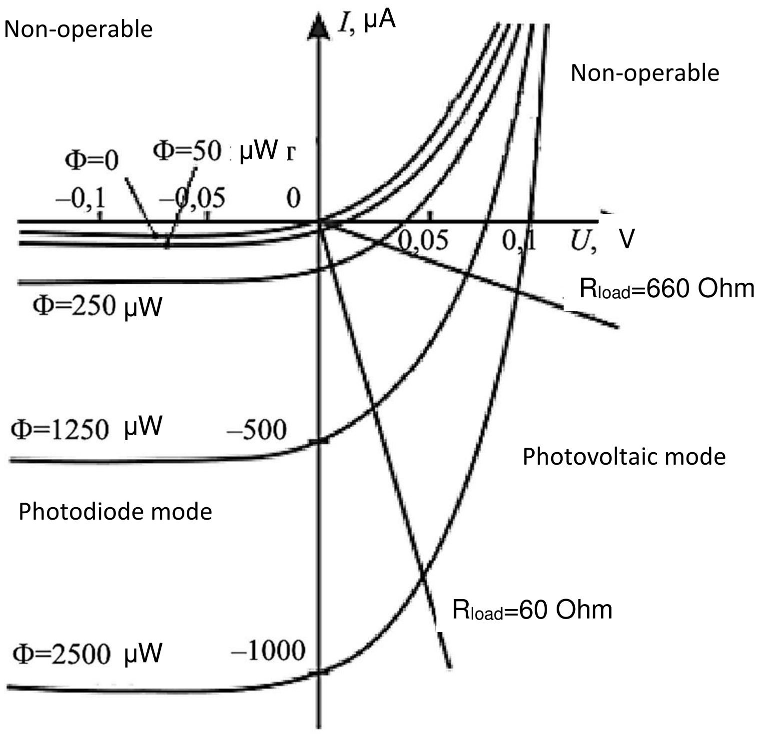


Figure 6.9 — Current-voltage characteristic of a photodiode

Voltage responsivity is expressed as

$$S_U = \frac{dU_{load}}{\mathrm{d}\Phi} = S_I \cdot R\,.$$

This expression illustrates that the higher the load resistance, the higher is the voltage responsivity of the photodiode. The maximum possible resistance depends on the maximum power which a photodiode can receive, so the equation for the maximum resistance is

$$R_{\max} = \frac{U_p}{\left(I_{\Phi\max} + I_s\right)} = \frac{U_p}{\left(S_I \Phi_{\max} + I_s\right)},$$

and the maximum voltage responsivity is

$$S_{U\max} = \frac{U_p}{\Phi_{\max} + \frac{I_s}{S_I}}.$$

In practical applications, if photocurrent $I_{ph}>>I_s$, then $S_{U\max} \approx U_p / \Phi_{\max}$, and if photocurrent $I_{ph}<<I_s$, then $S_{U\max} \approx S_I U_p / I_s$.

When a photodiode is operated with modulated radiation, it should have minimum voltage responsivity to DC (background signal) and maximum voltage responsivity to AC (object signal). The transformer circuit is often used for this application (Fig. 6.8b).

6.3 Fast-speed photodetectors

Photodiode time constant is defined by the time carriers pass from a thin surficial layer, where they are generated, the pn-junction, where they recombine, and by the RC time constant, as a photodiode is an RC-circuit.

To reduce the RC time constant, one can:

- reduce base thickness to let the carriers reach the pn-junction, where they recombine, faster;
- increase the pn-junction thickness by inverse voltage application to make radiation absorbed in the pn-junction;
- make the base transparent for the radiation received.

6.3.1 p-i-n photodiode

In a p-i-n photodiode, an instrinsic-type semiconductor is placed between the p- and n- region (Fig. 6.10). It increases the pn-junction thickness, according to principle 2 in the section above. Thus, radiation is absorbed in the i-layer, and in response to the electric field, the electron will travel to the right and the hole to the left. Time constant is defined by the travel time of a carrier to p- or n-region.

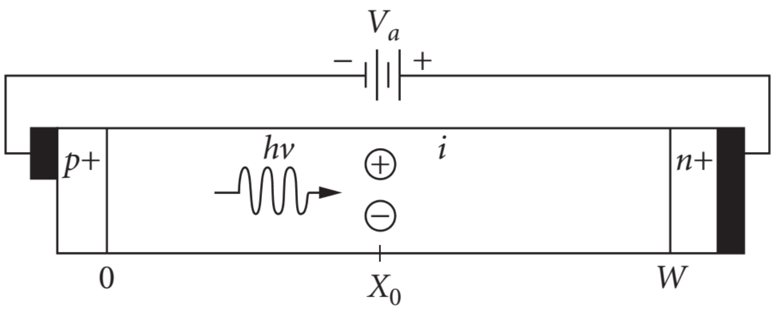


Figure 6.10 — p-i-n photodiode structure [1]

6.3.2 Schottky photodiode

The Schottky barrier photodiode is formed at a junction between a metallic layer and a semiconductor (Fig. 6.11). If the metal and the semiconductor have work functions related in the proper way, this can be a rectifying barrier. The junction is fabricated by oxidation of the silicon surface, then etching of a hole in the oxide, followed by the evaporation of a thin transparent and conducting gold layer. The insulation guard rings serve to reduce the leakage current through the device.

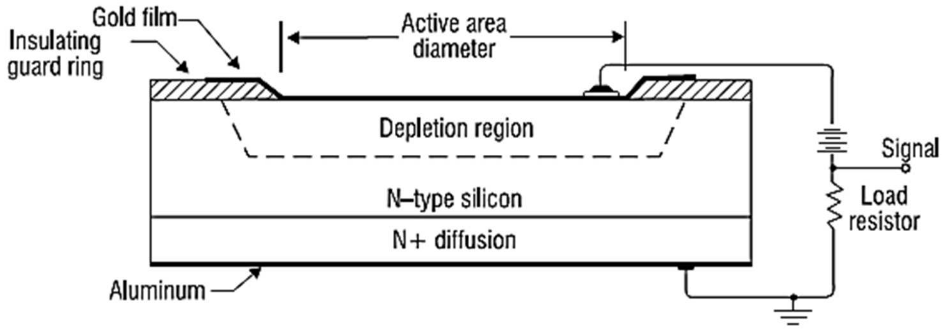


Figure 6.11 — Schottky photodiode structure [11]

6.3.3 Avalanche detectors

Avalanche detectors, or APDs, enhance the current by means of impact ionization process in pn-junction and avalanche generation of minor carriers (Fig. 6.12). In high reverse bias voltage electrons(A) collide with the lattice atoms in the pn-junction region, generating new electron-hole pairs (B–B′, C–C′, D–D′), which continue the process (child electrons B″, C″, D″ pulled off the lattice atom repeat the cycle). As a result, the output current will increase (perhaps 100–200 times greater than that of a non-avalanche device [11]). The detectivity is also increased, provided that the limiting noise is not from background radiation. The multiplication ratio of current increase is defined as

$$M = \frac{I_{out}}{I_{in}} = \frac{1}{1-\left(U_{pn} - U_{break}\right)} = \frac{1}{1-\left[\left(U_{p} - R_{load} I / U_{break}\right)\right]}.$$

As APDs work almost in breakdown mode, the multiplication ratio M is highly sensitive to the supply voltage U_p.

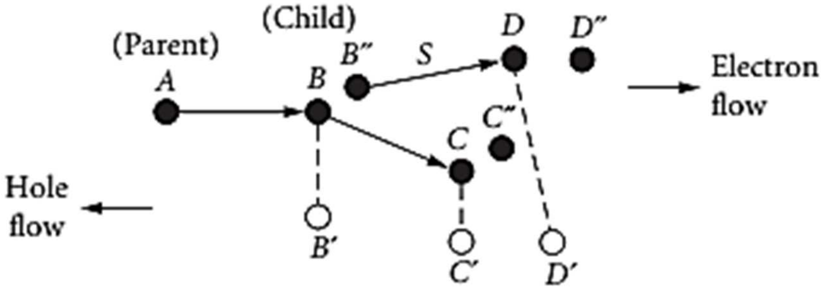


Figure 6.12 — Impact ionization process

High-speed GaInAs/InP APDs make use of separated absorption and multiplication layers (SAM APD). Fig. 6.13 shows the simplified one-dimensional APD structure. The narrow bandgap n-GaInAs layer absorbs the incident light. The layer is usually thick (>1 μm) to ensure high quantum efficiency. The electric field in the absorption layer is high enough for carriers to travel at saturated velocities, yet is below the field where significant avalanching occurs and the tunneling current is negligible. The wide bandgap InP multiplication layer is thin (a few tenths of a micron) to have shorter multiplication buildup time. The bias is applied to the fully depleted absorption layer to obtain effective carrier collection efficiency and, at the same time, electric field in the multiplication region must be high enough to achieve avalanche gain. A guard ring is usually added to prevent premature avalanche breakdown (or microplasma) at the corner of the diffusion edge. To reduce the hole pileup effect, a graded bandgap layer (e.g., superlattice or compositional grading) is often added at the heterointerface between the absorption layer and multiplication layer. This is the so-called separated absorption, grading, multiplication avalanche photodiode (SAGM APD).

Avalanche photodiodes cost more than conventional photodiodes and they require temperature compensation circuits to maintain the optimum bias, but they represent an attractive choice when high performance is required.

Besides APDs, there are other photodetectors that contain several pn-junctions and can enhance the current, such as phototransistors, field transistors and photothyristors.

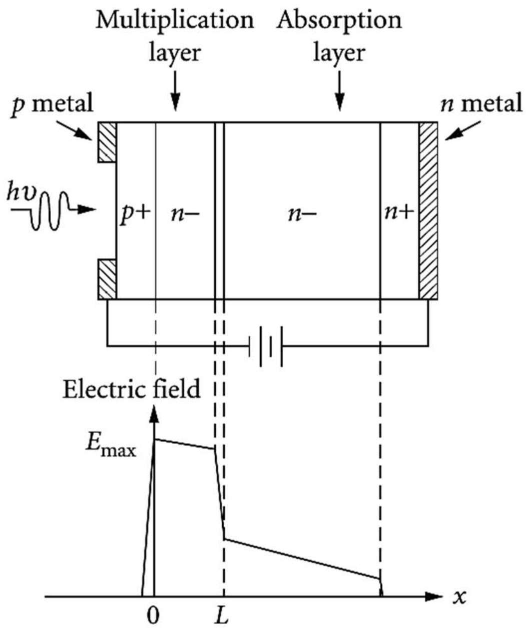


Figure 6.13 — Schematic diagram of an avalanche photodiode [1]

6.4 Photoemissive Detectors

The photoemissive effect involves the emission of electrons from a surface irradiated by quanta of light energy. A photoemissive detector has a cathode coated with a material that emits electrons when light of wavelength shorter than cutoff wavelength falls on the surface. The electrons emitted from the surface are accelerated by a voltage to an anode, where they produce a current in an external circuit. The detectors are enclosed in a vacuum environment to allow a free flow of electrons from anode to cathode.

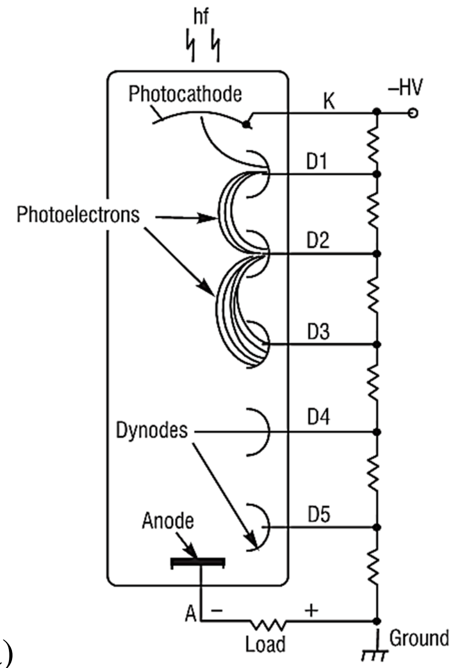
These detectors are available commercially from a number of manufacturers. They represent an important class of detectors for many applications.

Cathodes are often mixtures containing alkali metals, such as sodium and potassium, from which electrons can easily be emitted. At wavelengths longer than about 1000 nm, no photoemissive response is available. The short-wavelength end of the response curve is set by the nature of the window material used in the tube that contains the detector. The user can select a device that has a cathode with maximum response in a selected wavelength region [11].

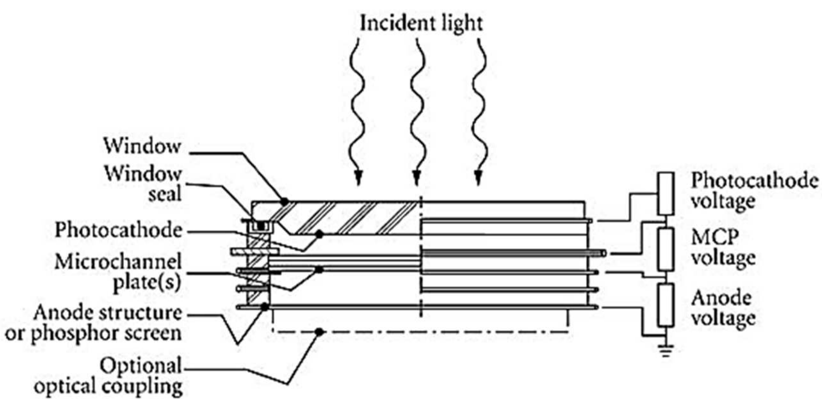
6.4.1 Photomultiplier

Photoemissive detector is generally the detector of choice in the UV, visible, and near-IR where high quantum efficiency is available. In the spectral region $\lambda<600$ nm, the photomultiplier, or multiplier phototube, has sensitivity close to ideal; that is, selected photomultiplier (PM) tubes can detect single photon arrivals (but at best only with about 30 percent quantum efficiency) and amplify the photocurrent (pulse) enormously without seriously degrading the signal-to-noise ratio. Time resolution can be as short as 0.1 ns. Only very specialized limitations have precluded their use for λ<800 nm, for example, cost, ruggedness, uniformity of manufacture, or need for still faster response. Recently, these limitations have all been met individually but generally not collectively. When adequate light is available, the simple phototube has advantages over the multiplier phototube, as high voltages are not required, the output level is not sensitive to applied voltage, and dynode fatigue is eliminated.

Microchannel plate (MCP) tubes are a variant of the photomultiplier tube where the current amplifying dynode structure is replaced by an array of miniature tubes, in which the photocathode current is amplified. MCP tubes are more compact than PM tubes and are reliable in operating conditions of high environmental stress. The same range of photocathode materials is available in MCP as PM tubes. MCP tubes can provide a wide range of electron gain as available, depending upon whether a single MCP or a stack of MCPs is used. Structures of a PM and MCP tubes are compared in Fig. 6.14 [1].



a)



b)

Figure6.14 – Comparison of photomultiplier(PM) tube (a) and microchannel plate (MCP) tube (b) construction [1]

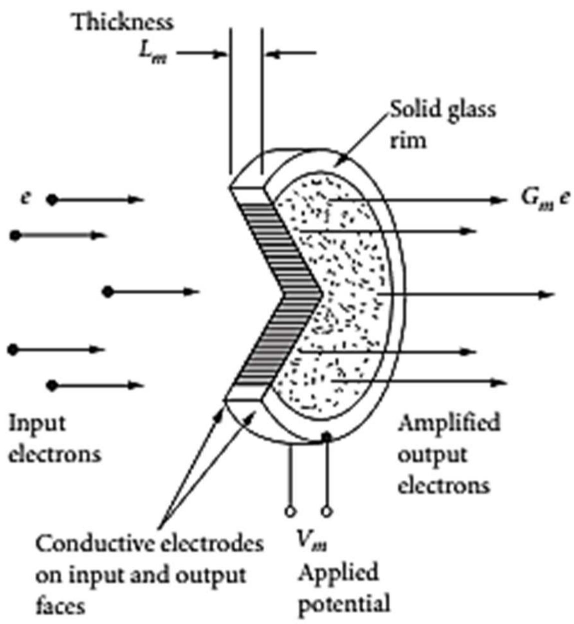


Figure 6.15 – Microchannel plate structure [1]

Spectral response of the photomultiplier is defined by cathode and envelope material. The multiplication ratio of the photomultiplier is defined by the anode total responsivity S_a devided by the cathode total responivity S_{cth} or relation of the anode dark current I_{da} to the cathode dark curren I_{dcth} :

$$M = \frac{S_a}{S_{cth}} = \frac{I_{da}}{I_{dcth}} .$$

The shot current (see Section 5.4.3) increases at each multiplication cascade (a pair of dynodes in Fig. 6.14a).

$$\overline{I}^2_{\text{shot}} = 2eI_{ctd}M^2\left(1+B\right)\Delta f ,$$

where $e = 1.6\times10^{-19}$ C is the electron charge, I_{ctd} is the cathode current, B is the shot noise ratio (depends on the photomultiplier type, for example, $1+B$ is typically 2.5 for a PM with electrostatic focusing), M is the multiplication ratio.

The dark current appears due to thermal emission of electrons from the photocathode and dynodes (the photocathode emission is the most important as its dark current is then increased in the PM), field emission, leakage current between the anode and other electrodes, etc.

The PM must be protected from external electromagnetic fields, as they influence on electron trajectories and modify the multiplication ratio. The photocathode and all the electrodes under voltage must not be excessively exposed as it can bring damage to the PM. When operating the PM with radiation power close to the NEP, it must be previously kept in darkness.

6.4.2 Image intensifier

The image intensifier is a vacuum-tube device (similar to the vidicon) that accepts an image at one end and produces an image of higher intensity at the other. The image intensifier can be considered an image amplifier that uses energy to achieve the necessary amplification. These devices are used in low-light-level situations such as night vision and astronomy. Image intensifiers were first developed to work with vidicons and other early electronic camera technologies and were often manufactured as components of these cameras. Modern image intensifiers are used as adapters to cameras or by themselves as night-vision devices under starlight conditions.

The image-intensifier tube has a photocathode screen at one end and a phosphor screen at the other end as shown in Fig. 6.16. The photocathode is a material, such as gallium arsenide, that emits electrons when exposed to light. An optical system is used to image a scene onto the photocathode, and electrons are emitted in proportion to the amount of light imaged. The electrons are accelerated by an electric field, which produces gain in terms of number of electrons at the phosphor screen. When the electrons strike the phosphor screen, the screen emits visible light and produces an intensified image on the photocathode screen of the scene formed at the input end of the tube.

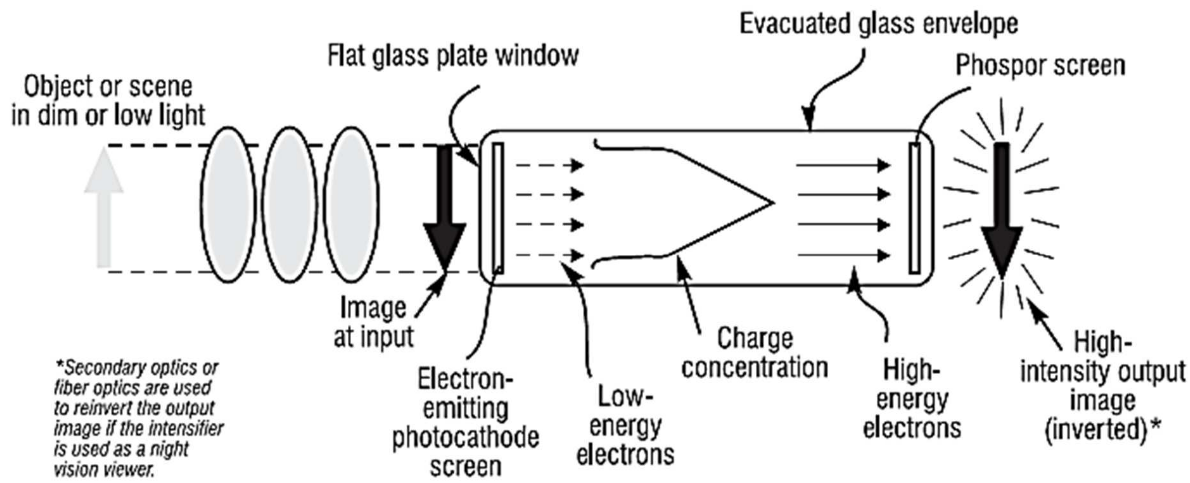


Figure 6.16 — Image intensifier [11]

The electro-optical intensifier can also be connected in consequence or combined with photomultiplication devices mentioned above, either dynodes or microchannel plate (this configuration is used in most cases). Thus, the enchancemet ratio increases.

7. THERMAL DETECTORS

Thermal detectors respond to the total energy absorbed, regardless of wavelength. Thus, thermal detectors do not have a long-wavelength cutoff in their response, as photon detectors do. The value of D* for a thermal detector is independent of wavelength. Thermal detectors generally do not have as rapid a response as photon detectors do. For many photonics applications, they are often not used in the wavelength region, in which photon detectors are most effective ($\leq$1.55 μm). They are often used at longer wavelengths.

7.1 Bolometers and thermistors

Bolometers and thermistors are thermal detectors, where optical energy is absorbed by an element, whose properties change with temperature. As light energy is absorbed, the temperature of the element increases and the change in its properties is sensed. Bolometers and thermistors respond to the change in electrical resistivity as temperature rises. Bolometers use metallic elements, while thermistors use semiconductor elements. The bolometer or thermistor is put in a circuit in series with a voltage source, so that current flows through it and, as the resistance changes, the voltage drop across the element changes, providing a sensing mechanism. Bolometers are connected into the circuit like photoconductors (see Fig. 6.4). The radiant flux to be received by bolometers is usually modulated. This allows AC amplifiers to be used.

There are several different types of bolometers, including thermistor, semiconducting, superconducting, carbon, and metallic. They may also be subdivided according to operation temperature, room or cryogenic.

Metal bolometers have a linear change in resistance with temperature, that may be expressed as

$$R = R_0\left[1 + \alpha_T\left(T - T_0\right)\right],$$

where α is thermal coefficient. This coefficient always decreases with temperature, and burnout does not occur. The coefficient is approximately equal to the inverse of the temperature, and is never very high. Therefore, the change in resistance is expressed as

$$\Delta R = R_0 \alpha_T \Delta T \ . \tag{7.1}$$

The increment of the signal from the bolometer, connected to the circuit, as in Fig. 6.4(a), is defined. The current in the circuit is

$$I = V_{ps} / (R + R_l),$$

where V_{ps} is the power supply voltage, R_l is the load resistance. If the flux changes by $\Delta\Phi$, the resistance and, therefore, the current, change by

$$dI = -V_{ps} dR / (R + R_l)^2 .$$

From the equation (7.1), $\Delta R / R = \alpha_T \Delta T$, the change in current is

$$dI = -\frac{V_{ps} dR \cdot R}{(R + R_l)^2 R} = -V_{ps} \alpha_T \Delta T \frac{R}{(R + R_l)^2},$$

$$dV = dIR_l = -V_{ps} \alpha_T \Delta T \frac{R \cdot R_l}{(R + R_l)^2}.$$

The maximum total responsivity is achieved at $R=R_l$.

Semiconductor bolometers have an exponential change of resistance with temperature, given by

$$R = R_0 e^{\beta/T}.$$

The value of β depends on particular material. These detectors can burn out. Two basic types exist: (1) those that are used at low temperatures and (2) those that are used at about room temperature.

The most frequently used low-temperature bolometers are germanium in a bath of liquid helium. Pure germanium is transparent in the infrared, but with enough compensated doping it becomes a good conductor with a high-temperature coefficient of resistance. Typical concentrations are about 10^{16}cm^{-3} of gallium and 10^{15} of indium. Even these are not sufficient at wavelengths shorter than 10 μm, since the free-carrier absorption is proportional to wavelength. In such a case a black coating is sometimes used.

Superconducting bolometers make use of the extremely large thermal coefficient of resistance at the transition temperature. Originally, they needed to be controlled very carefully, or a small change in ambient conditions (on the order of 0.01 K) can cause an apparent signal of appreciable magnitude. A more recent version incorporates an evaporated thin film on an anodized aluminum block, that is coupled to a helium bath by a brass rod. The detector has a time constant of about 3 μs due to this high thermal conductance and a good NEP of about 10^{-13} WHz$^{-1/2}$. It still must be controlled to about 10^{-5} K, and this is accomplished with a heater current and control circuit.

Recently developed materials not only have high-temperature transition points but also have more gradual transitions, and provide a better compromise between good responsivity and the requirement for exquisite control.

Carbon Bolometers are a form of semiconductor bolometers that have been largely superseded by germanium bolometers. They are made of small slabs of carbon resistor material, connected to a metal heat sink with a thin mylar film. Although their responsivities are comparable to germanium bolometers, their noise is several orders of magnitude higher.

7.2 Thermocouples

The thermocouple is a device formed of two dissimilar metals joined at two points and is attached to a light absorbing element. Thermocouples may be fabricated from wires, but for detector applications they are often fabricated as thin films. The device generates a potential difference, which is a measure of the temperature difference between the points. One point is held at a constant reference temperature. The second point is in contact with the absorber. The light energy heats the absorber and the thermocouple junction in contact with it. This causes the voltage generated by the thermocouple to change, giving a measure of the temperature rise of the absorber and of the incident light energy.

To enhance the performance of the thermocouples, often there are a number of thermocouples in series, perhaps as many as 100. The "hot" junctions are all attached close together. This type of device is called a thermopile.

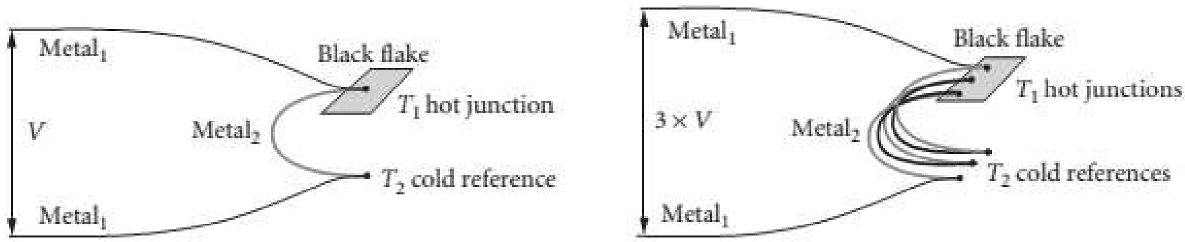


Figure 7.1 – a) Thermocouple detector structure; b) Thermopile detector structure [1]

7.3 Calorimeters

Pulse energy is frequently measured with a calorimeter, which represents a common thermal detector system. Calorimetric measurements yield a simple determination of the total energy in an optical pulse, but calorimeters usually do not respond rapidly enough to follow the pulse shape. Calorimeters designed for photonics measurements often use blackbody absorbers with low thermal mass and with temperature-measuring devices in contact with the absorber to measure the temperature rise. Knowledge of the thermal mass coupled with measurement of the temperature rise yields the energy in the optical pulse.

A variety of calorimeter designs have been developed to measure the total energy in an optical pulse or for integrating the output from a continuous optical source. Since the total energy in a pulse is usually not large, the calorimetric techniques are rather delicate. The absorbing medium must be small enough that the absorbed energy may be rapidly distributed throughout the body. It must be thermally isolated from its surroundings so that the energy is not lost.

A commonly encountered calorimeter design, the so-called cone calorimeter, uses a small, hollow carbon cone, shaped so that radiation entering the base of the cone will not be reflected back out of the cone. Such a design is a very efficient absorber. Thermistor beads or thermocouples are placed in contact with the cone. The thermistors form one element of a balanced bridge circuit, the output of which is connected to a display or meter. As the cone is heated by a pulse of energy, the resistance of the bridge changes, leading to an imbalance of the bridge and a voltage pulse that activates the display. The pulse decays as the cone cools to ambient temperature. The magnitude of the voltage pulse gives a measure of the energy in the pulse. Two identical cones may be used to form a conjugate pair in the bridge circuit. This approach allows cancellation of drifts in the ambient temperature.

7.4 Pyroelectric detectors

Pyroelectric detectors respond to the change in electric polarization that occurs in certain classes of crystalline materials (like lithium tantalate) as their temperatures change. The change in polarization, called the pyroelectric effect, may be measured as an open-circuit voltage or as a short-circuit current.

As they respond to changes in temperature, pyroelectric devices are useful as detectors for only pulsed or chopped radiation. The response speed of pyroelectric detectors is fast, faster than that of other thermal detectors, like thermistors and thermopiles. Pyroelectric detectors are fast enough to detect very short optical pulses.

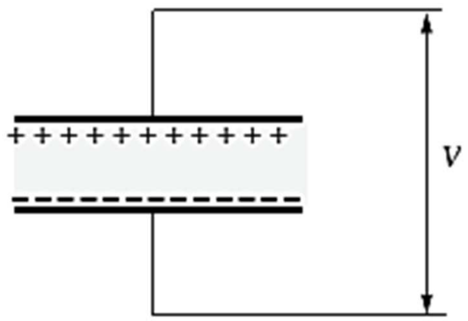


Figure 7.2 – The pyroelectric effect produces a surface charge when the temperature changes

8. IMAGING SENSORS

8.1 Charge-coupled-devices (CCD)

Charge-coupled device (CCD) cameras are the most pervasive of imaging devices present. A CCD camera uses an array of light-sensitive cells formed in silicon. The cells can be thought of as miniature capacitors, where each capacitor is a pixel in the image created by the array. When the array is exposed to light, the capacitors charge up proportional to the intensity of the light falling on the array. This charge, which is discriminated by values of voltage, is then read off the array, converted to a digital signal, and transferred into a computer.

CCD cameras have electronic shutters that control the integration time at each pixel. This means that the charging time of the capacitor is controlled. The longer the capacitor is charged, the more time the pixel will have to charge. Exposure in the camera is also dependent on the device physics used in the CCD array construction. Most cameras have automatic exposure controls that operate to the limits of the camera specifications, and limit the electrical signal output by the camera or hold the signal to a constant value. More sophisticated cameras allow adjustments to be made under computer control and are equipped with special interface units [11].

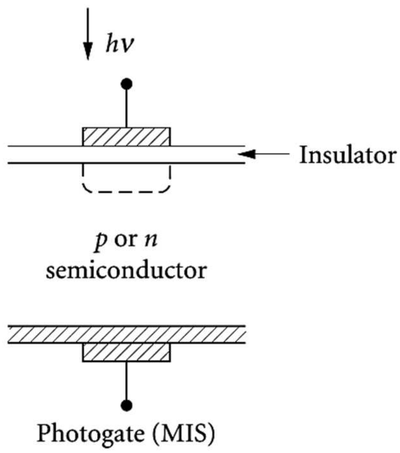


Figure 8.1 – Metal-insulator-semiconductor structure

CCD Operation. The CCD works by moving packets of charge physically at or near surface of silicon from the image-sensing element to an output, where the charge packet is converted into voltage. The CCD is formed by an array of overlapping metal-oxide-semiconductor (MOS) capacitors. There are different types of CCDs, including four-phase, three-phase, two-phase, virtual (single-) phase, and ripple-clocked CCDs.

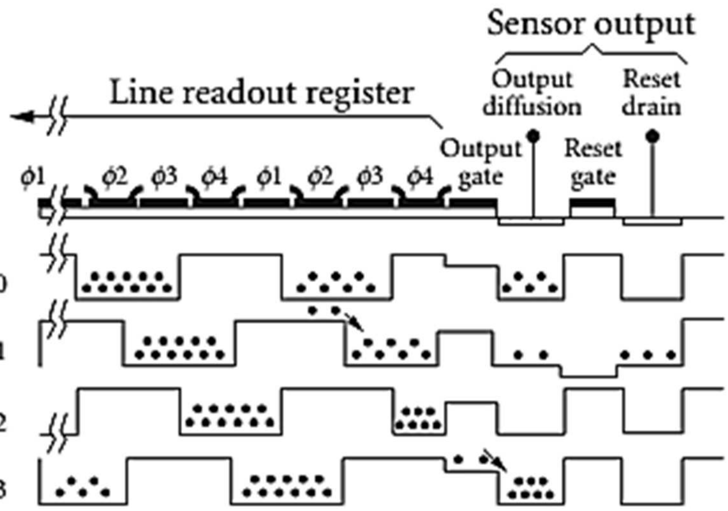


Figure 8.2 – Transmission of charge packets in a CCD line

The process of charge transfer in a four-phase CCD is illustrated in Fig. 6c. To hold a packet of electrons, two adjacent gates (φ_2 and φ_3, for example) would be held at a high positive potential (~+5 V), while the other two phases would be held at a low potential (~0 V). A depletion layer, or well, is formed under φ_2 and φ_3, allowing electrons to be held at or below the surface. The other two phases, φ_1 and φ_4, serve as potential barriers, keeping the charge packet under φ_2 and φ_3. To transfer the electrons through silicon, the electrode ahead of the charge packet (φ_4) is clocked positive and the electrode behind (φ_2) is clocked negative. The electrons move along the silicon surface following the positive potential. This procedure is repeated through all four phases, and the charge packet is moved one pixel forward.

8.2 Linear Image Sensor Arrays

There are three basic architectures for linear sensing arrays: MOS line arrays, CCD linear and multilinear sensors, and time-delay and integrate (TDI) sensors. These architectures are illustrated in Fig. 8.3: (a) MOS line array consisting of photodiodes, preamplifier, MOS switches addressed by an address register, and a readout line with amplifier; (b) linear CCD image sensor consisting of photodiodes, transfer gate, and CCD readout; (c) linear CCD image sensor with two CCD output registers, one for the odd diodes and the other for the even diodes, for higher horizontal pitch;(d) staggered linear CCD image sensor with two rows of photodiodes offset by one-half pixel to increase horizontal sampling; (e) trilinear CCD in which three CCDs are fabricated on the same silicon die, each with its own color filter; and (f) time-delay and integrate (TDI) array, in which the charge in the vertical registers is clocked in phase with the motion of the scene or document being imaged in order to increase signal-to-noise.

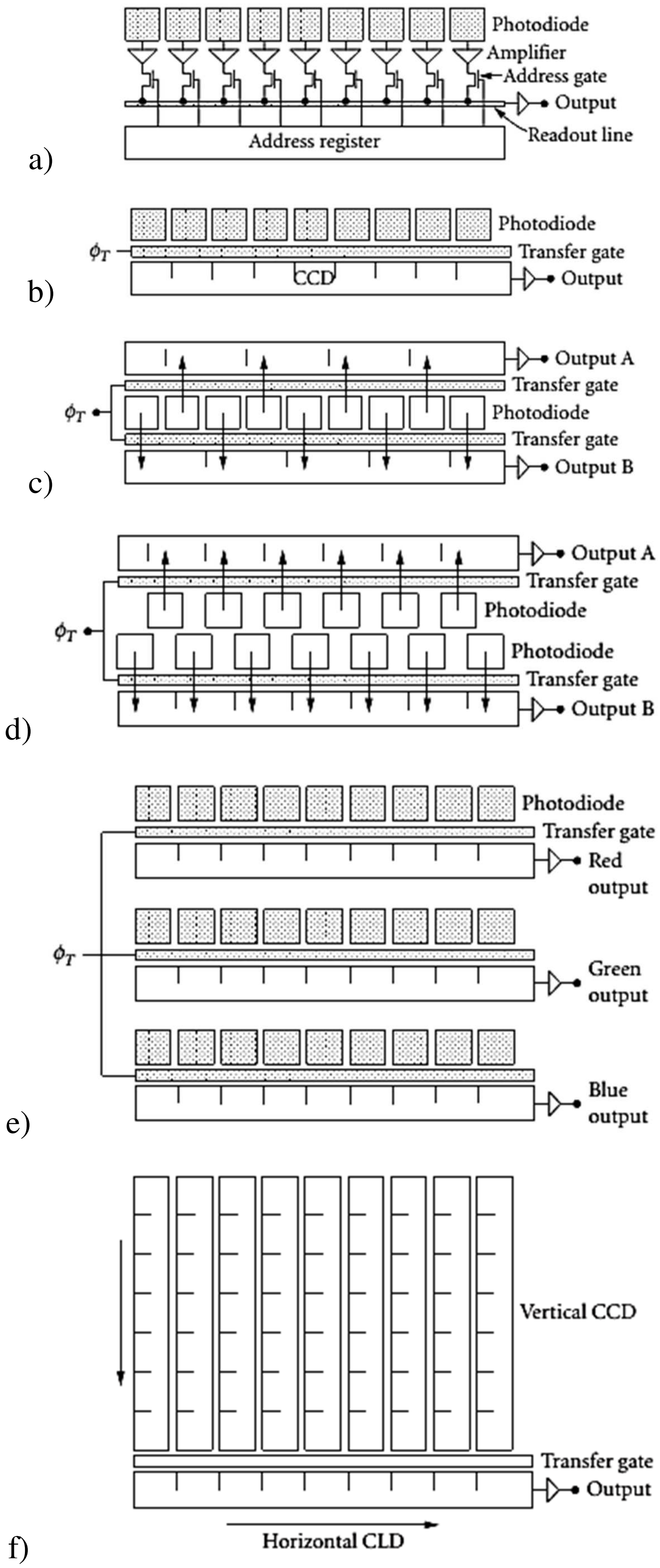


Figure 8.3 — Architectures for linear image sensors

8.3 Area Image Sensor Arrays

There are three major classes of area image sensor architectures: MOS diode arrays, frame-transfer CCDs, and interline-transfer CCDs. Each of them may have some variations though. CCDs are mostly operated when higher sensitivity is required. However, MOS arrays are applied when addressability or high readout rate is important [1].

8.3.1 MOS Area Array Image Sensors

The architecture of MOS area arrays is illustrated in Fig. 8.4. It consists of the imaging array, vertical and horizontal address registers, and output amplifiers. The pixel of a MOS array consists of an image-sensing element (photodiode, photocapacitor, phototransistor, or photoconductor), a row-address gate, and a vertical readout line. The row-address gate is bussed horizontally across the array and is driven from a row-address register on the side(s) of the array. At the start of a line, a single row is addressed, causing the charge from all the photodiodes in a row to be transferred onto the vertical readout line. Horizontal address gates are placed at the bottom of the vertical readout line. Buffer amplifiers to drive the horizontal readout line may also be placed at the end of the vertical readout line. The horizontal address register then serially addresses each vertical readout line, sequentially turning on the horizontal address gates. When the horizontal addressing is completed, the readout lines may be reset and precharged, and the next row is addressed.

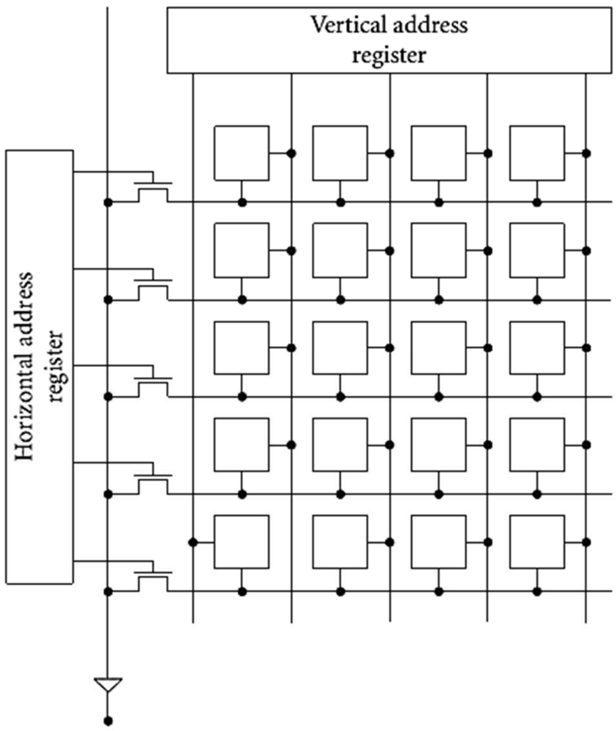


Figure 8.4 — Architectures for linear image sensors MOS photodiode array, consisting of vertical and horizontal address registers and readout line

8.3.2 Frame Transfer CCD Image Sensors

CCD area arrays fall into two categories: frame transfer and interline transfer. The simplest form of frame transfer CCD is the full-frame type, shown in Fig. 8.5a. The array consists of a single image area composed of vertical CCDs and a single horizontal register with an output amplifier at its end. In this architecture, the pixel consists of a single stage of a vertical CCD. This type of device requires an external shutter. When the shutter is opened, the entire surface of the sensor is exposed, and the charge is collected in the CCD potential wells at each pixel. After the shutter is closed, the sensor is read out a row at a time by clocking a row of the vertical register into the horizontal register, then clocking the horizontal register to read out the row through the output amplifier. For higher readout rates dual horizontal CCDs are used in parallel. The full-frame CCD has the advantage of progressive scan readout, high fill factor, very low noise, and wide dynamic range. However, it requires an external shutter. It is most often used in still electronic photography, scientific, industrial, and graphics applications [1].

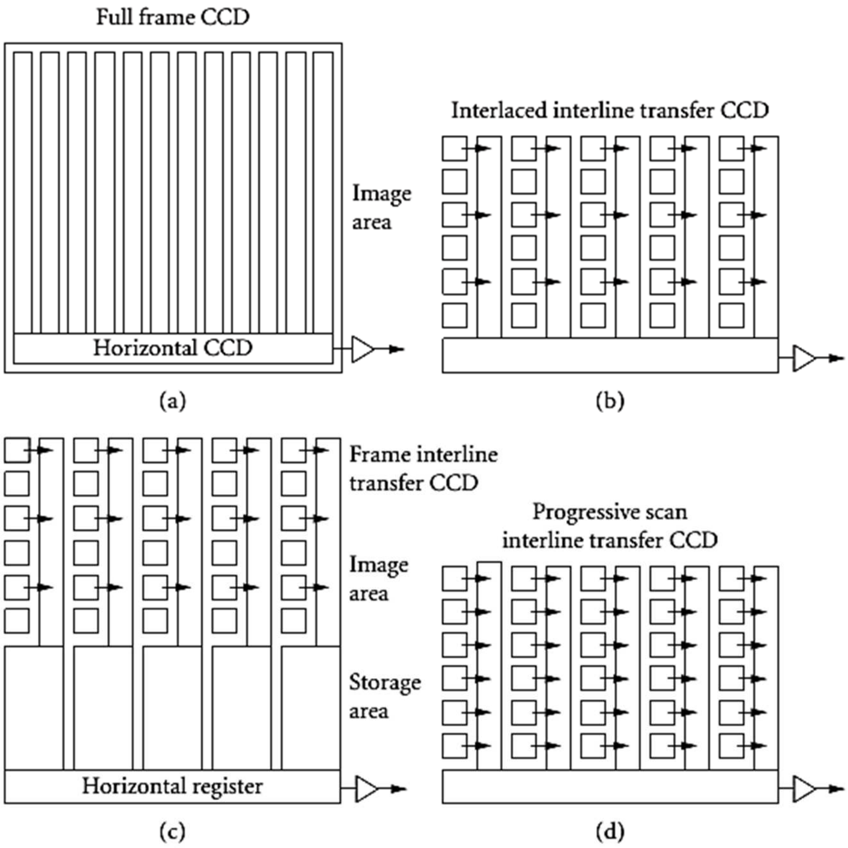


Figure 8.5 — (a) Architecture of full-frame CCD; (b) architecture of interlaced interline transfer CCD; (c) architecture of frame interline transfer CCD, in which a storage area is provided to reduce smear during readout; and (d) progressive scan interline transfer CCD, in which every photodiode is read out into the vertical CCD simultaneously

For motion imaging applications, a shutter is not practical. To overcome the need for a shutter, frame transfer CCDs incorporate a storage area in addition to imaging area. For interlaced video applications, this storage area is sufficiently large to hold a field (242 lines in NTSC television).

The device operates as follows. The image area integrates for a field time and the photogenerated charge is held in the vertical CCDs. The vertical CCDs are then clocked in order to rapidly transfer the charge from the image area into the storage area. Because the sensor is still under illumination, this transfer time must be much shorter than the integration time. This transfer typically requires 0.2 to 0.5 ms. The storage area is then read out a row at a time by transferring a row into the horizontal register and clocking this register. While this readout, the image area is integrating the next field. The most significant disadvantage of frame transfer CCDs is the image smear caused by illumination while transfer from the image to the storage area. This smear can be on the order of 3 percent.

MOS and CCD readout differ in an important way. In a MOS readout, the charge is transferred from a single pixel onto a readout line and the change in voltage or current in the readout line is sensed. In a CCD, the charge packets are kept intact while being transferred physically to a low-capacitance output.

CCD readout has very high sensitivity and low noise. However, CCD readouts are limited in charge-handling capacity. MOS readouts are capable of carrying very large amounts of charge and so have higher dynamic range. However, because the MOS readout line has much higher capacitance than that of the CCD, the sensitivity is lower and the noise is higher. CCD and MOS also have different readout architecture. The CCD readout is serial, it means that random readout or partial-array readout is not available. The MOS array, however, can be addressed in a manner similar to a memory, making it well-suited to pixel or partial-array addressing.

8.4 Resolution and Spatial Frequency

Resolution relates to the fineness of detail the image represents, or the fineness of detail the camera records or the display system displays. The more pixels per unit area the image has, the higher the resolution. The term resolution comes from the word resolve, which the dictionary defines as “to break up into constituent parts.” There are several ways to define resolution in terms of imaging. One way is by using the following equation: Resolution = number of pixels/area. For an image that is 3 × 3 inches square and contains 900 by 900 pixels, the resolution is (900 × 900)/(3 × 3) = 9000 pixels per square inch. This sort of measure is difficult to visualize, and so an alternative expression, that is more common, defines resolution in terms of lines per distance. Usually the resolution of a commercial CCD camera or television is stated in terms of lines. Many inexpensive CCD cameras have 380 lines; this means that the sensor array has 380 rows of sensors. If the CCD array — the electronic chip — is 1⁄4" wide, resolution = number of lines/length = 380 lines/0.25 inch = 1520 lines per inch. If a one-inch square is drawn on a piece of paper, with lines on the square, the lines drawn must be as thin as 1⁄1520 of an inch, and the CCD must resolve them. This assumes, however, that a 1⁄4" subsquare is imaged onto the CCD array due to the size of the array. However, only 760 lines can be resolved, which is one-half of 1520. The reason for this is that we need to have a black line, then a white line, then a black one, and so on alternate. To display a line, a sensor for the line and a sensor for the space between that line and the next line, i.e. two sensors per line are needed, which gives rise to the division by two of the resolution. In sampling theory, the Nyquist rate is the rate, at which a signal is sampled in order to capture all its frequencies, and this rate is twice the highest frequency that must be sampled. Frequency shows how often something changes in time. When something changes in distance, like pixels or lines per inch, we call this spatial frequency. Spatial frequency is a more specific term than resolution, even though they share the same units. Typically, images have resolutions that are represented as pairs of numbers, indicating the number of rows and columns in pixels of the image—although the actual size in terms of length or area of the image is not mentioned. Common computer display resolutions are 512 by 512, 1024 by 1024, and 2048 by 2048 for square images and 640 by 480, 800 by 600, and 1024 by 768 for rectangular images. High definition television, or HDTV, is 1080 by 1920 pixels.

8.5 Color imaging

Silicon based CCDs are monochrome in nature. That is, they have no natural ability to determine the varying amounts of red, green, and blue (RGB) illumination presented to the photodetectors.

There are three techniques to extract color information.

1. Color Sequential (Fig. 8.6a). A color image can be created using a CCD by taking three successive exposures, while switching in optical filters with the desired RGB transmittances. This approach is normally used only to provide still images of stationary scenes. The resulting image is then reconstructed off-chip. The advantage to this technique is that resolution of each color can remain that of the CCD itself. The disadvantage is that three exposures are required, reducing frame times by more than a factor of three. Color misregistration can also happen due to subject or camera motion. The filter switching assembly also adds to the mechanical complexity of the system.

2. Three-Chip Color (Fig. 8.6b). Three-chip color systems use an optical system to split the scene into three separate color images. A dichroic prism beam splitter is normally used to provide RGB images. Color images is then be detected by synchronizing the outputs of the three CCDs. The disadvantage to such a system

is that the optical complexity is very high and registration between sensors is difficult.

3. Integral Color Filter Arrays (CFA) (Fig. 8.6c). Instead of performing the color filtering off-chip, filters of the appropriate characteristics can be fabricated above individual photosites. This approach can be performed at a device fabrication using dyed (e.g., cyan, magenta, yellow) photoresists in various patterns. The major problem with this approach is that each pixel is sensitive to one color only. Off-chip processing is required to "fill in" the missing color information between pixels.

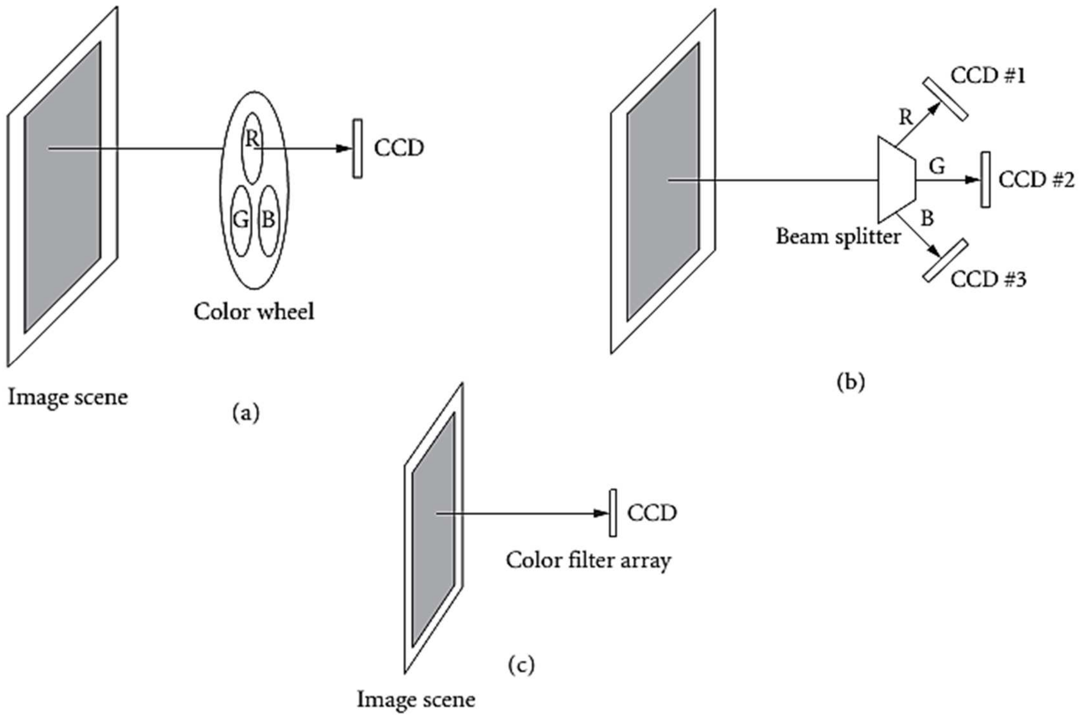


Figure 8.6— Color imaging technique [1]

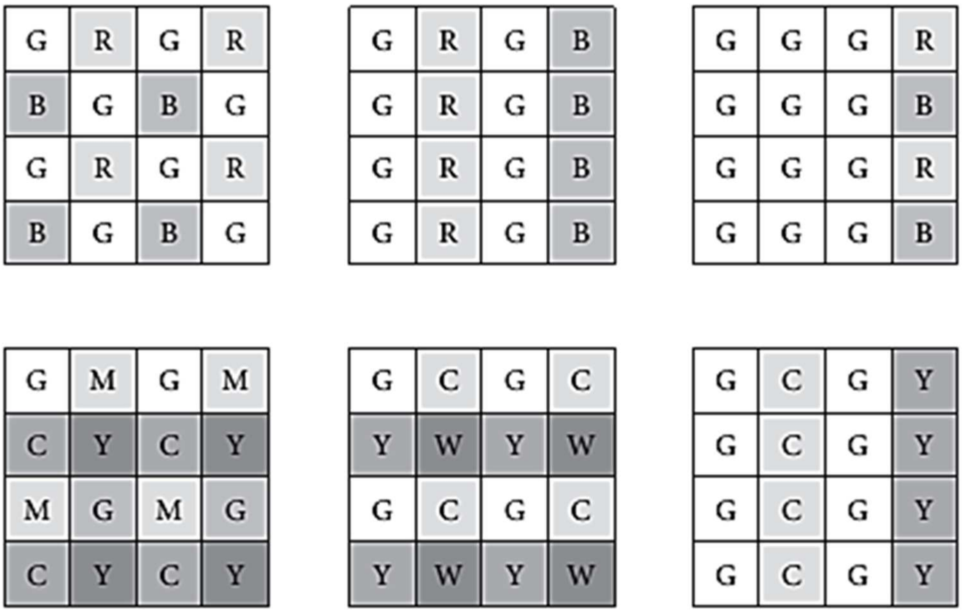


Figure 8.7— Common color filter patterns where, R=Red, G=Green, B=Blue, Y=Yellow, M=Magenta, C=Cyan, and W=White [1]

To minimize size, weight, and cost, most consumer color camcorders use a CCD sensor with an integral CFA. The photosites are covered with individual color filters—for example, a red, green, and blue striped filter, or a green, magenta, cyan, and yellow mosaic filter. Some popular CFA patterns are shown in Fig. 8.7. As each photosite senses only one color, the color sampling is not coincident. For example, a blue pixel might be seeing a white line, while nearby red and green pixels are seeing a dark line in the scene. As a result, high-frequency luminance edges can be aliased into bright color bands. These color bands depend not only on the color filter pattern used, but also on the optical prefilter and CFA interpolation algorithm.

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1958–1967 — Department of special optical devices,
1967–1992 — Department of optical-electronic devices,
Since 1992 — Department of optical-electronic devices and systems.

The Department has been managed by:

1938–1942 — Professor K. Solodilov,
1942–1945 — Professor A. Zakharievsky,
1945–1946 — Professor M. Rezunov,
1947–1972 — Professor S. Zukkerman,
1972–1992 — Honored Scientist of the RSFSR, Professor L. Porfiriev,
1992–2007 — Honored Scientist of Russia, Professor E. Pankov,
Since 2007 till present — Honored worker of higher professional education, Professor V. Korotaev.

From 1938 to 1970 the department was part of the Optical Faculty.

In 1970 the department became a part of the Faculty of Optical-Electronic Engineering, which was renamed into Engineering-Physical Faculty in 1976.

In 1998, the department became a part of the Faculty of Optical-Information Systems and Technologies.

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- optical inspection methods,
- measuring video systems,
- surveillance video systems,
- surveillance video systems for fast moving objects,
- thermal vision imaging surveillance systems,
- technosphere safety optical-electronic systems,
- optical-electronic devices for nonstationary deformable objects control,
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- color and spectral analysis optical-electronic devices and systems.

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