OPTICAL FIBER SENSORS

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Summary

Extraordinarily rapid development of methods of data transmission using fiber optics has taken place in the last quarter of the twentieth century. Fiber transmission lines allow transfer of very great data arrays to any region of the globe at a very high rate. At the same time, optical fibers can serve as sensors of magnetic and electric fields, the mechanical stresses and acceleration of a system, as well as its position in space, and velocity. In this article, we consider the operation of sensors of various physical parameters (radiation, magnetic field, current, frequency, amplitude, and phase), based on optical fiber, as well as the design of detectors for measuring parameters of radiation transmitted by fibers. Concrete designs of fiber sensors, sources, and detectors are presented.

1. Introduction

Humankind, being a self-governing system, has developed a great variety of self-regulating mechanisms, machines, and systems. Measurement, that is, the most important process of any physical parameter control, is carried out by an instrument called as a measured value sensor, for example, the temperature sensor (thermometer). Optical fiber sensors (OFS) have been developed with the advent in the 1970s of the technology of fiber lightguides capable of channeling light. Physical values are measured in OFS via light, that is, electromagnetic waves of the optical band.

OFS are applied to measure various physical values, for example, the temperature, velocity, acceleration, electric and magnetic fields, and electric current. During these measurements, the electromagnetic wave of the optical band interacts with a medium, in which it propagates. A measured physical value is either a parameter of this medium (for instance, temperature) or acts upon the medium via one or another physical field (for instance, a magnetic one), reorganizing the medium structure. Hence, the result of that interaction depends on a measured physical value.

Information carried by optical radiation can to be written in terms of the following characteristics of the optical electromagnetic wave: (i) amplitude (or intensity), (ii) frequency, (iii) phase, and (iv) polarization. Each characteristic separately and in any combinations can be used by OFS to measure physical values. The use of one or another characteristic determines the method for detecting optical radiation and extracting information on a measured physical value.

The interaction with an electromagnetic wave is controlled by the following macroscopic parameters of a medium: (i) refractive index, including birefringence, (ii) transmission (absorption, gain), including optical dichroism and lasing, and (iii) characteristics of nonlinear transformations of radiation. The optical band is typical of the interaction between an electromagnetic wave with electrons of a medium where radiation propagates. Electron clouds in various materials have a great variety of physical properties, which cause a variety of OFS. The interactions between electrons of a medium with electromagnetic waves can be described simply enough using the medium dielectric constant tensor and the transmission (absorption, gain) tensor. These can be combined into a unified tensor of the complex dielectric constant.

OFS consist of: (i) a sensitive element, (ii) a source and (iii) receiver of optical radiation, (iv) a fiber lightguide (FL) carrying radiation from the source to the sensitive element and to the receiver, (v) a data processing unit, and (vi) an indicator. Sometimes the sensor is understood only as a sensitive element. We believe that a detection method is essential for understanding an instrument operation and including this in the proper OFS concept.

Such sensors are characterized by the absence of metal wires, which offer a number of advantages as compared to ordinary electric sensors:

- a wide band (up to terahertz);
- the minor loss of FLs, hence, long distances between a receiver–transmitter and an object where the sensitive element is placed (and measurements are carried out);
- mechanical strength of FLs (the tensile strength is up to 7 kg);
  absence of crosscoupling;
- zero inductance (the impact of electromagnetic induction is virtually absent, as well as negative phenomena caused by lightning discharges, closeness of power transmission lines, and current pulses in supply lines); and
- explosion safety (absolute inability of FLs to cause a spark)Let us consider sensor units in more detail.

2. Radiation Sources and Receivers

We present the general characteristics of the radiation sources used in OFS. The source features typical of concrete sensors are considered in the next sections.

2.1. Electromagnetic Wave Properties

The electric field of an electromagnetic wave plays a determining role in the interaction with electrons of a material. The electric field wavevector **E** is written as

$$\mathbf{E}(x,y,z,t) = \mathbf{E_o} \cos(\omega t - n\mathbf{kr} + \phi), \qquad (1)$$

where ($\omega t - \mathbf{kr}$) is the wave phase, $\omega = 2\pi\nu = 2\pi/T$, is the angular frequency (radians per second), ν is the number of oscillations per second, $\nu\cdot\lambda = c$, c is the velocity of light, T is the oscillation period, t is the current time, n is the refractive index of a homogeneous environment, **k** is the wavevector (($|\mathbf{k}| = 2\pi/\lambda$, λ is the wavelength in vacuum, **r** is the current radius vector drawn from the radiation source point to an observational point, and ϕ is the initial wave phase. The wavevector **k** is orthogonal to the wavefront and indicates the wave propagation direction.

The vector $\mathbf{E_o}$ is as a rule perpendicular to the propagation direction and controls wave polarization. If the vector $\mathbf{E_o}$ oscillates in a single plane in the course of wave propagation, the wave is said to have a linear polarization. If the vector $\mathbf{E_o}$ rotates with the frequency ω counterclockwise or clockwise (looking along the vector $\mathbf{k}$) during propagation, the wave is said to have right- or left-hand circular polarization, respectively. When there exist both linear and circular polarizations at various proportions, it is thought that polarization is elliptic.

The squared amplitude E_o^2 is proportional to the wave energy density at a given point and defines the radiation intensity. Square-law detectors absorb energy by portions (quanta), hence, are responsive to E_o^2. The human eye also responds to the squared amplitude of an electromagnetic wave.

Electromagnetic wave (Equation 1) is no better than an idealization. Any source emits a set of electromagnetic waves differing by frequencies ω_i (respectively, $\mathbf{k_i}$) and initial phases ϕ_i,

$$\mathbf{E}(x,y,z,t) = \sum_{i=1}^{N} \mathbf{E_{oi}} \cdot \cos(\omega_i t - n\mathbf{k_i r} + \phi_i) \tag{2}$$

Noteworthy as this sum is, a vector and the cosine periods are different. Generally speaking, it is impossible to extract information from Equation 2, stored in wave phases and frequencies, since corresponding methods are based on the interference phenomenon. Thus, the *coherence* becomes an important characteristic of the radiation source. The source coherence is determined by the visibility function V of an interference fringe pattern at the difference δ between optical lengths passed by two interfering beams from a given source,

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{\sin x}{x}, \tag{3}$$

where I_{max} and I_{min} are the maximum and minimum fringe intensities,

$$x = \pi \cdot (\Delta\omega/\omega) \cdot (\delta/\lambda) \tag{4}$$

It is evident that the smaller the ratio $\Delta\omega/\omega$, the greater is the function V at the fixed path difference δ, where $\Delta\omega$ is the frequency scatter in the set of source waves; in other words, various frequencies ω_i in Equation 2 lie near a certain average frequency ω_o, $\omega_o - \Delta\omega < \omega_i < \omega_o + \Delta\omega$. A source is believed to be coherent if the visibility function (interference pattern contrast) suffices to detect the phase shifts.

2.2. Incoherent Sources

The simplest radiation source is the incandescent lamp where the electric current energy is converted into heat in a thin wire and then is emitted according to the laws of blackbody (Planckian radiator) emission. The blackbody emission spectrum for temperatures of incandescent lamps extends from the visible region to the infrared one and has a maximum at wavelength $\lambda \approx 2200$ nm. The transmission window of quartz fiber lightguides is 200 nm $< \lambda <$ 1650 nm. Therefore, most of the incandescent lamp power is released irrationally. However, the low price of such sources allows their application as simple sensors.

The light-emitting diode is an incoherent light source. It represents a p–n junction between a p–semiconductor with an empty conduction band and a n–semiconductor with a filled conduction band. The forbidden band between the valence and conduction bands is 1÷3 eV, which corresponds to a quantum energy of the visible and near infrared regions. At currents 10 ÷ 100 mA at the p–n junction, electrons appear in the conduction band of p–semiconductor and recombine with holes of the valence band, which have an excessive concentration. The recombination is accompanied by spontaneous emission of an energy quantum with no preferable direction. The emission spectrum is wide enough ($\Delta\lambda \sim 100$ nm) and is controlled by spreading the forbidden band edge. The radiation power (up to ~ 50 mW) is proportional to the injection current through the diode, which is convenient for radiation intensity modulation. The radiation directivity is same as for the Lambert source, $I \sim \cos^2\theta$, where θ is the angle between an observational direction and the normal angle to the emitting surface.

Active layer	Casing	Sustrate	Range of wavelengths, nm
ZnSSe		GaSb	200 ÷ 500
AlGaInP	AlGaInP	GaAs	500 ÷ 600
GaInAsP	GaInP	GaAs	550 ÷ 950
AlGaAs	AlGaAs	GaAs	650 ÷ 950
GaInAsP	InP	InP	950 ÷ 1700
AlGaAsSb	AlGaAsSb	GaSb	1050 ÷ 1700

Table 1. The combination of semiconductor materials of light-emitting diodes

The transmission spectrum of fiber lightguides is spanned by the combination of semiconductor materials of light-emitting diodes listed in Table 1.

Because of their small sizes and simple control of radiation intensity, light-emitting diodes are basic devices used as light sources in OFS and not based on radiation coherence.

2.3. Coherent Sources and Semiconductor Lasers

As coherent sources for OFS, stimulated radiation sources (lasers) are used. By virtue of the small size of the luminous surface, semiconductor (injection) lasers are most appropriate for injecting radiation into FLs. In this case, the same semiconductor materials as for light-emitting diodes (see Table 1) are employed for the same spectral regions. Radiation is stimulated by an optical resonator, that is, the Fabry–Perot interferometer. The resonator mirrors are cleavage planes of a semiconductor crystal. In this case, the fact that the refractive index of the semiconductor materials is very high (n

> 3) plays an important role. Currently, diffraction gratings introduced into laser planar lightguides are employed as mirrors of highly coherent injection lasers.

The lasing starts at a certain injection current referred to as the threshold. It characterizes thermal loss and leads to heating of the laser chip. This in turn raises the threshold current, which can result in the lasing collapse (shut-down). The lower the threshold current (10–20 mA), the higher the laser quality. Furthermore, heating shifts the lasing frequency, particularly in the absence of gratings. Therefore, the laser should be mounted on a heat-removing device to stabilize the laser chip temperature. Typically, this is a Peltier element.

The laser coherence degree is controlled by a lasing linewidth. In the case of single-frequency, single-mode lasers without gratings, with gratings, and with special devices for narrowing the line, the linewidths and Q-factors are respectively $\Delta\nu \sim 100$ MHz, 1 MHz, and 10 kHz; $Q = \nu/\Delta\nu \sim 10^6$, 10^8, and 10^{10} . The injection laser aperture is controlled by the diffraction divergence $\theta = \lambda/d$, where d is the mode spot size at the laser output. Routinely, $\theta \sim 20^o$. The typical laser power is 10–50 mW, although more powerful multimode lasers (up to 1 W) exist. When designing sensors, one should consider nonlinear effects which can arise at high powers of highly coherent radiation, injected into FLs.

2.4. Fiber Lightguides

Optical waveguides in the form of glass fibers are taken up in sensors as a radiation-transmitting medium and the sensors' sensitive elements. Fiber lightguides are characterized by very small radiation loss and low dispersion, which allows the use of broadband signals of the optical band. The loss *L* in optical fibers is measured in decibels per kilometer by the formula

$$L = (10/L_f)\cdot\log(I_{in}/I_{out}) \text{ (dB/km)} \qquad (5)$$

where I_{in} and I_{out} are radiation intensities at the input and output of a fiber section of length L_f km. In contrast to communication optical fibers, loss requirements for fibers used in sensors are much lower. A loss $L < 100$ dB/km is acceptable, which allows the use of, for example, quartz fibers in the whole range of their transparency (from 200 nm to 1.65 μm).

The initial materials for producing optical fibers are mainly high-transparency and rather homogeneous glasses made of fused quartz with a very low impurity concentration. The material purity can be easily evaluated due to the fact that a loss source in lightguides is the Rayleigh scattering, rather than absorption of uncontrollable impurities. At a wavelength of 1.55 μm, the record-breaking loss is $L \approx 0{,}02$ dB/km. This loss grows in inverse proportion to the quartic wavelengths, $L \sim 1/\lambda^4$, and only when near λ =200 is the Rayleigh scattering changed by a band of quartz fundamental absorption.

The fundamental absorption band at the long-wave spectral edge originates from 1.65 μm. The typical spectrum of quartz lightguide loss is shown in Figure 1. The absorption peaks at λ =1.4 μm and 900 nm are caused by overtones of oscillatory transitions of water, or more correctly, of OH groups.

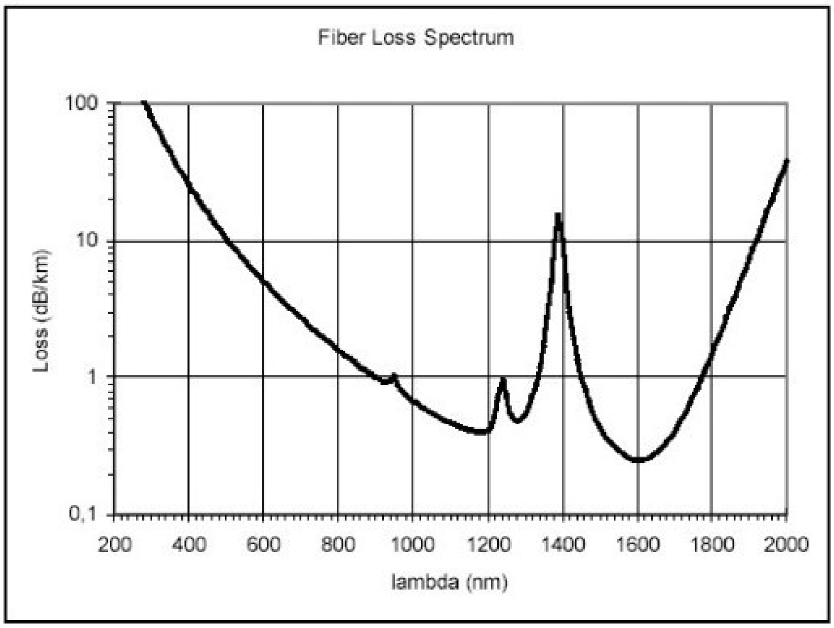

Figure 1. The typical spectrum of quartz lightguide loss

The fiber lightguide core is surrounded by a light-reflecting cladding of an equally pure material as the core, differing only by a lower refractive index. Light propagates in such a two-layer fiber according to the total internal reflection at the core–cladding interface. As a rule, a plastic coating is applied onto the light-reflecting cladding to raise its strength and to protect it against environmental impact. The coating often contains components absorbing radiation passing from the core into the cladding.

Spatial constraints for waves propagating in the lightguide by core boundaries leads to discrete directions, along which this wave can propagate, as well as the impossibility of propagation in other directions. This means that waves propagate as separate modes in fibers. Various modes occur onto the core–cladding interface at different angles and their optical paths are different in the same lightguide section. Single- and multimode fiber lightguides are recognized. The number N of modes in a multimode lightguide can be roughly estimated as

$$N = k^2a^2(n_c^2 - n_o^2) / 2 \qquad (6)$$

where a is the core radius, $k = 2\pi/\lambda$ is the wavevector, n_c and n_o are the core and cladding refractive indices, respectively. The number N of modes is about 1000 in a conventional fiber with a core diameter of 50 μm and a cladding outer diameter of 125 μm. The wavefield distribution in the single-mode fiber core is a bell-shaped curve whose wings are beyond the core (in the cladding). This means that the wave propagates partially in the light-guiding cladding; hence, the latter should be sufficiently thick. Single-mode lightguides are characterized by the cutoff wavelength λ_c of the second mode. If the used light wavelength is shorter than the cutoff wave ($\lambda < \lambda_c$), two modes propagate in the fiber. The wavelength λ_c can be determined by the dimensionless parameter V of the fiber,

$$V = ka\cdot(n_c^2 - n_o^2)^{1/2} \quad (7)$$

If V< 2.405, a single-mode condition is maintained in a fiber. When radiation is injected into the lightguide, one should match emitter and fiber apertures. The sine of the maximum incidence (onto a fiber face) angle still corresponding to a channeled mode is referred to as the numerical aperture NA

$$NA = V/ka = (n_c^2 - n_o^2)^{1/2} \quad (8)$$

The fiber axial symmetry allows propagation of two modes, differing by their polarization, under single-mode conditions.

However, moderate random tensions always take place in ordinary coherent fibers, hence regions with random orientation of birefringence axes arise. Therefore, linearly polarized light in such a lightguide becomes elliptic with randomly varied ellipticity and directions of the ellipse principal axes. Such lightguides do not suit polarization sensors, for which special single-mode lightguides maintaining polarization are employed. These are classified into two types: with low and high birefringence (LB and HB).

LB fibers are produced by the fast rotation of a blank in the course of its pulling. The rotation period is significantly shorter than the section length where the random birefringence varies. Therefore, roughly speaking, the mode of one polarization lags behind another for one half of the period and catches up with it for the second half of the period during light propagation. The phase delay between the two modes in period varies slightly (about 4^o); on average it is zero over many periods. Such fibers conserve polarization well and can be used in polarization sensors. The quality of such lightguides is controlled by the beat length L_b reaching a few kilometers for good fibers,

$$L_b = 2\pi/[k(n_x - n_y)] \quad (9)$$

where $(n_x - n_y)$ is the residual difference of the refractive indices for waves polarized along the principal axes x and y, which is a result of uncompensated birefringence.

On the other hand, HB fibers are produced with strong internal tensions and high ellipticity of the core. Therefore, birefringence is so strong that the beat length L_b reaches 3–5 mm. Light polarized along one of the principal axes in such lightguide light, remains parallel to this axis even if the latter progressively turns lengthwise. A quality characteristic of such a lightguide is the parameter H defining a fraction of power transferred from the mode polarized along one of the axes into the mode with orthogonal polarization at the lightguide section of length 1 m. The typical value of H is about 10^{-5}.

2.5. Receivers of Optical-Band Radiation

Since information on a measured value can be stored in various light wave parameters, detection methods differ significantly. We consider these methods in the next sections. In this section, we enlarge on the general characteristics of receivers found in all detection schemes.

2.5.1. Square-Law Detector

Though the radiation behavior in vacuum and matter is described as wave propagation, the interaction between radiation and matter proceeds under quantum laws, that is, the energy is transferred by energy quanta $\Delta E = h\nu$, where ν is the light frequency and h is the Planck constant. This interaction is also characteristic of light radiation detectors. Threshold electron detectors are most commonly used, where an electron cannot participate (for example, be a carrier) in any process until it gains an energy exceeding one or other work function. The total detector current J is a combination of photocurrent J_{ph}, that is, the electron current injected by optical radiation, and the spurious dark current J_d. The detector has a delayed action characterized by the measuring time τ_m during which $\tau_m >> 1/\nu$. Let the energy absorbed in the measuring be W. Then the number $N_e = \eta\cdot W/h\nu$ (where $\eta< 1$) of electrons maintaining the photocurrent, that is, the quantum yield, is the parameter reflecting the fact that the electron does not necessarily arise in the photocurrent although the photon is absorbed. The average photocurrent is given by

$$J_{ph} = (1/\tau_m)\cdot(e\eta W/h\nu) = (e\eta/h\nu)\cdot P \qquad (10)$$

where P is the average radiation power absorbed in the detector. P is written in terms of the light wave parameters. If the detector area is S, radiation is incident onto it perpendicularly and the energy density of the wave electric field is $u = \varepsilon E^2(t)/8\pi$. Then the energy absorbed in the detector in the time dt is written as

$$dW = u\cdot S\cdot c\cdot dt = (cS\varepsilon/8\pi)\cdot E^2(t)dt \qquad (11)$$

where c is the velocity of light. The average power of absorbed radiation is given by

$$P = (cS\varepsilon/8\pi)\cdot(1/\tau_m)\cdot \int_0^{\tau_m} E^2(t)dt, \qquad (12)$$

Therefore, detectors responding to absorbed power are referred to as square-law ones. One of the most perfect detectors in the optical band, that is, the human eye, is also a square-law detector with a long delayed action (τ_m = 1/16 s). We consider detection of a wave with an oscillation frequency of 10^{15} Hz by the inertial detector. Let the light wave field be described by Equation 1, then we have

$E^2(t) = E_o^2\cdot\cos^2(\omega t + \varphi)$ at the detector and the average power P is given by

$$P = (cS\varepsilon/8\pi)\cdot(1/\tau_m)\cdot\int_0^{\tau_m}(1/2)\cdot E_o^2\cdot[1 + \cos(2\omega t + 2\varphi)]dt \tag{13}$$

The integral of the cosine of the double frequency over time $\tau_m >> 1/\nu$ is zero; therefore, P is independent of measuring time and the average radiation power absorbed in the detector is proportional to the squared wave amplitude, $P \sim E_o^2$. The detector current is written as

$$J = \gamma\cdot E_o^2 + J_d \tag{14}$$

where $\gamma = (ecS\varepsilon\eta/16\pi h\nu)$. The dark currents J_d of various detectors have a different nature; this problem will be discussed below.

2.5.2. Photodiodes

The internal photoconductive effect, that is, interband motion of carriers that absorbed light, is employed in photodiodes. The contact potential difference at the p–n junction prevents initiation of the majority carrier current. Equilibrium minority carriers maintain a moderate so-called dark current in the negative portion of the diode current–voltage characteristic. Nonequilibrium minority carriers of photocurrents arise during absorption of light quanta. Consider Figure 2. Before producing the p–n junction, we have two extrinsic semiconductors with equilibrium p-type carriers (holes) in the valence band and n-type carriers (electrons) in the conduction band (a). The Fermi level is given by a dashed line. After formation of the p–n junction, the band structure arises (b). majority carriers, for example, electrons of the n-type semiconductor, should overcome an energy barrier to arrive at the empty conduction band of the p-type semiconductor. Then minority carriers, for instance, electrons thrown into the conduction band at thermal motion in the p-type semiconductor, easily migrate down into the conduction band of the n-type semiconductor and give rise to a dark current. Figure 2 (c) shows the interband transition at photon absorption and the formation of nonequilibrium minority carriers responsible for the photocurrent J_{ph}.

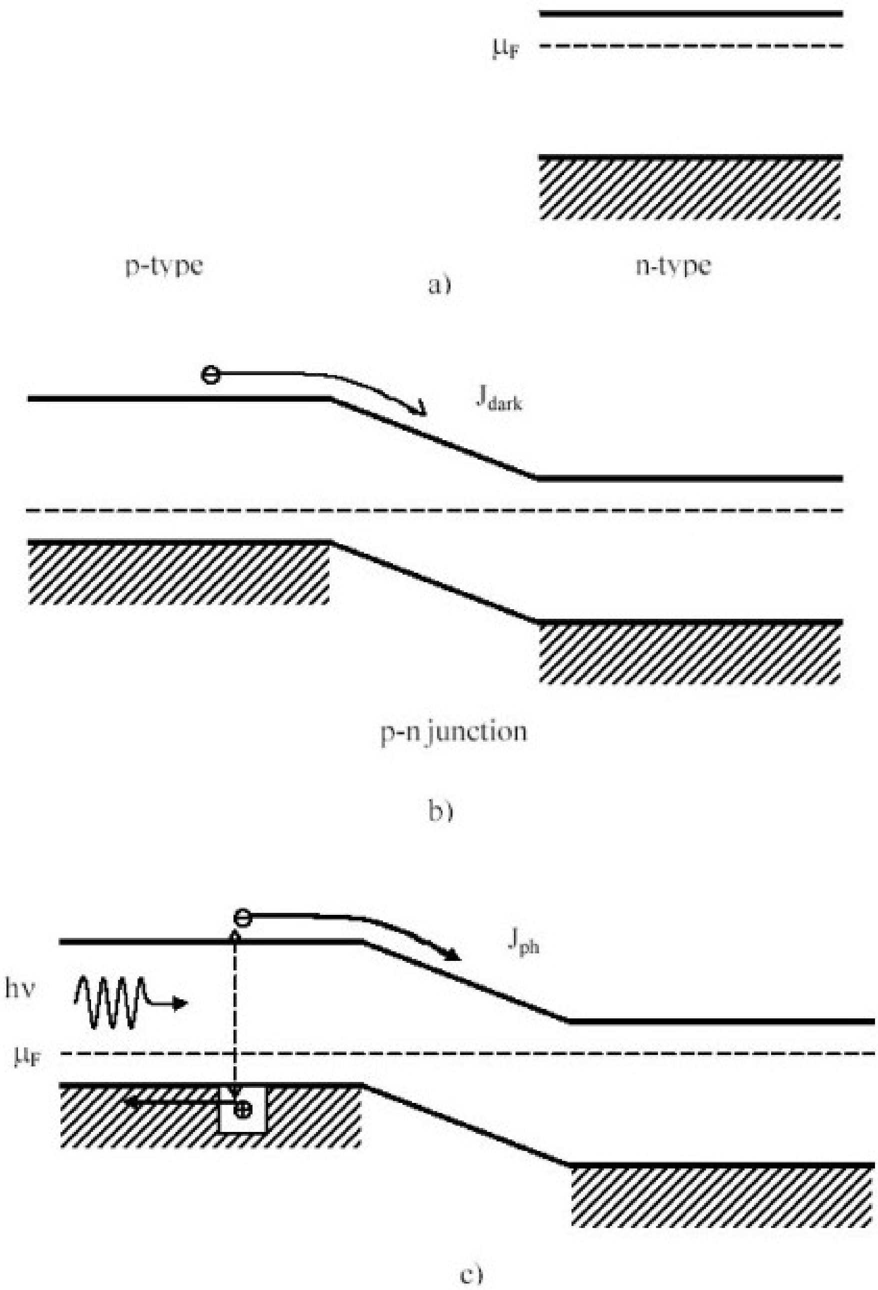

Figure 2. The internal photoconductive effect. a) two extrinsic semiconductors with equilibrium p-type carriers (holes) in the valence band and n-type carriers (electrons) in the conduction band; b) the contact potential difference at the p–n junction prevents initiation of the majority carrier current; c) the interband transition at photon absorption and the formation of nonequilibrium minority carriers responsible for the photocurrent Jph.

Ge, Si, GaAs, InP, and other semiconductors can be used as detectors. Since each material has an intrinsic band gap E_g, the maximum wavelength λ_{max}, to which the detector can respond has a fixed value ($h\nu \geq E_g$),

$$\lambda_{max} = c \cdot h / E_g \qquad (15)$$

For example, silicon photodiodes do not respond to light radiation with $\lambda > 1$ μm. As for semiconductors composed of three or four elements of III–IV groups of the periodic system ($Ga_{1-x}Al_xAs$ and $In_xGa_{1-x}As_yP_{1-y}$), the value E_g can be controlled by varying x and y. Thus, a photodetector responding to light of a certain wavelength in a wide band can be developed.

The photodiode sensitivity is limited by various noises. The отношение сигнал – шум signal-to-noise ratio is given by

$$S/N = 2J_{ph}^2 / [2e(J_{ph} + J_d)B + 4kT \cdot F \cdot B/R_{in}] \qquad (16)$$

where B is the radio frequency spectrum width, k is the Boltzmann constant, T is the temperature, and R_{in} is the input resistance of the amplifier to which the diode is connected. The value $2e(J_{ph} + J_d)B$ defines the shot noise caused by electron production frequency fluctuations in time under the action of light. The value $4kT \cdot F \cdot B/R_{in}$ defines the thermal noise power at the first amplifier stage. To increase the sensitivity and response speed, one should thicken the depleted layer by increasing the inverse bias voltage to reduce the junction capacitance.

An interesting version of photodetectors based on photodiodes is the avalanche photodiode in which the photocurrent can be amplified. As the inverse bias grows, diffusion of the carriers is amplified simultaneously with the thickening of the depleted layer, and a band with a strong electric field about 100 kV/cm arises near the p–n junction. In this band, diffusion electrons collide with neutral atoms, knocking out secondary electrons. These are accelerated in the strong electric field and collide again, producing new electrons, that is, an avalanche current growth is observed. The gain is controlled by increasing the number of electrons. Avalanche diodes are excellent detectors due to their high sensitivity and short delayed action; however, these require an increased and stable inverse bias. Furthermore, the noise increase with the gain should be diminished.

2.5.3. Photoelectronic Multiplier

The photoelectronic multiplier represents a vacuum device whose receiving face (photocathode) is coated by a material characterized by a photoeffect with a low work function. The device contains a large number of dynodes whose potential monotonically increases to the output. Photoelectrons produced by illumination of the photocathode are accelerated in the field of the first dynode and knock out from it secondary electrons with a multiplication factor exceeding unity. Then they are accelerated in the field of the second dynode, knock out secondary electrons again, and so on. Thus, an electron avalanche controlling the photocurrent arises at the photoelectronic multiplier output. The device has a high sensitivity and can operate even in the solitary photon counting mode. However, photoelectronic multipliers are scarcely used in OFS due to the necessity of a high voltage (a few kilovolts) and corresponding power supplies.

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Cross-references

(see: *Blackbody Radiation, p-n Junction, Valence and Conductive Band, Circular Polarization, Elliptic Polarization, Interference, Spontaneous Emission, Birefringence, Fermi Level, Photoeffect, Optoelectronics*)

Biographical Sketch

Sergei Konstanatinovich Morshnev graduated at Moscow Institute of Physics and Technology in 1967. Since 1970 he has worked at the Institute of Radiotechnique and Electronics, Russian Academy of Sciences, currently as a leading scientific researcher. His received his scientific degree in physico-mathematical sciences in 1978. His thesis was devoted to the investigation of the dynamical orientation of nuclei in molecular crystals.
In 1977 S.K. Morshnev and coauthors received the diploma to certify the discovery of the independence of the electron subsystem temperature in electron paramagnetic resonance.
The main scientific interests of S.K. Morshnev lie in the investigation of states in molecular crystals excited by light, and in the study of physical properties of optical fibers that are intensively used for transferring information. S.K. Morshnev is the author of seven inventions devoted to various applications of fibers as sensors of different physical parameters.
At present S.K. Morshnev is working on a fiber that could conserve a primary polarization of the signal.