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ULTRAVIOLET, INFRARED, AND TERAHERTZ OPTICS

Optical Materials for the THz Range

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Abstract—The properties of optical materials usable in the terahertz (THz) spectral range, which is the boundary between the optical and radio ranges, are examined. The relevance of the research field associated with the optics of THz devices is largely governed by intensified activity on creating lasers operating in the THz range and the discovery of substantial problems in the use of optical materials for these applications in general. The present study is devoted to analyzing the properties—especially optical properties—of the THz materials used. The characteristics are given, and the physical, chemical, and optical properties of conventional and new materials, including crystalline (silicon, sapphire, quartz, diamond, germanium, and silicon carbide), as well as a number of polymers (polymethylpentene, polyethylene, and polytetrafluoroethylene), are discussed and compared.

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INTRODUCTION

Electromagnetic waves in the spectral range of 0.1–10 THz (3 mm–30 μm, 3–300 cm^{-1}), lying between the microwave and far infrared ranges, are commonly referred to as terahertz (THz) radiation.

The boundaries between types of radiation are defined differently in different sources. The maximum allowable THz frequency range is 10^{11}–10^{13} Hz and, accordingly, the wavelength range is λ = 3.0–0.03 mm. If the wavelength is in the range of 1–0.1 mm, then such waves are also called submillimeter waves or *T*-waves. The THz range is the boundary between the optical and radio ranges. Many applications of the THz range noticeably lag behind the applications of neighboring regions of the electromagnetic spectrum, i.e., the microwave and optical ranges. If the methods of studying the high-frequency part of the THz range are closer to those used for the optical and infrared ranges, then the low-frequency part of this range is usually investigated by the radiophysics methods [1–4]. The radiation spectra of astronomical objects and the spectra of complex organic molecules (such as proteins, DNA, some explosives, hazardous substances, air pollutants, etc.) lie in the THz region.

In comparison with visible or infrared waves, THz radiation can better penetrate turbid and finely dispersed media, for example, leather, plastics, clothes, or paper, as a result of the drastic suppression of Rayleigh scattering ($1/\lambda^4$). Due to the low photon energy, it does not cause damage characteristic of ionizing radiation (such as X-rays). Therefore, the possibility of replacing X-ray machines by THz sources is actively sought in medicine. *T*-waves do not penetrate metals. These properties can be used in current production control (for example, in drug production), quality control of finished products, and THz thermal imaging. The development of THz spectroscopy to characterize semiconductor materials and devices, chemical composition analysis, biochemical studies, remote detection of explosives, toxic substances, and addictive drugs, etc., is of great interest [5–7]. The development of THz radio detection is significantly constrained by the lack of powerful THz radiation sources with satisfactory weight-size characteristics [1–4].

Until recently, laser technology has hardly been used to produce THz radiation, although the possibility of creating a THz laser was demonstrated for the first time in 1970 [8]. There are a number of reasons for such a limited scope, in particular, inadequate understanding of the advantages of this range over other ranges, low efficiency of the designed lasers, underdevelopment of the instrumental and metrological base for this range, the absence of good optical materials, and high absorption of THz radiation in the atmosphere. Nevertheless, comparatively convenient—albeit narrow—transmission regions are currently found in a more detailed study of the propagation of THz radiation in the atmosphere. Relatively high atmospheric attenuation even in transparency windows nonetheless leaves sufficient possibilities for various applications of THz radiation not only in vacuum, but also under atmospheric air pressure [1].

Compact THz radiation sources are low-powered (in the μW–mW range) [9]. For example, quantum-cascade lasers based on AlGaAs/GaAs heterostructures, the Gunn diode, avalanche-transit diodes, resonant-tunneling diodes, etc. It is reported in [10] that laser radiation with $\lambda = 750$ μm is obtained in a *p*-type Ge crystal at the temperature of liquid helium. The sources that use the electrooptical effect in photoconducting materials with picosecond charge carrier relaxation times, for example, in semiconductor crystals, require the use of femtosecond pulse lasers, which cannot be called compact lasers.

Long-wavelength THz radiation (about 3 mm) with an average power of about 1 MW is obtained in gyrotrons. Gyrotrons were designed in the 1960s, used in tokamaks, and are actively used now in an international project to construct a thermonuclear experimental reactor (ITER project). They are electric vacuum microwave devices in which the flow of electrons rotating in a uniform external magnetic field at frequencies close to the cyclotron frequency or its harmonics generates THz radiation [11].

The principal studies of powerful coherent *T*-waves are carried out in the area of lasers with optical pumping. The theoretical limit of the efficiency of this kind of THz lasers obeys the Manley–Rowe relation [12]. Theoretical assumptions are reported in [13] that the Manley–Rowe conversion limit,

$$\varepsilon = \frac{\nu_{\mathrm{FIR}}}{2\nu_{\mathrm{IR}}},$$

where ε is the efficiency of pumping radiation conversion in THz, ν_{IR} is the THz radiation frequency, and ν_{FIR} is the frequency of pumping photons, can be substantially exceeded through cascade processes when the dispersion of group velocities of optical pulses is small. The typical efficiency values are around 10^{-4}–10^{-3}.

As is seen from the Manley–Rowe law, as much as possible long-wave radiation is energetically most advantageous to use for pumping the THz media. Among the most common pumping sources, these are CO_2 lasers, which have an efficiency of about 10% [12, 14]. There are two major ways of using optical pumping to generate relatively powerful THz laser radiation: pumping of gas media, among which several hundred media have been studied and from which several thousand lines have been obtained [15], and generation of waves with a difference frequency in nonlinear crystals [14, 16–18].

The allocation of waves with a difference frequency in nonlinear crystals is accompanied, owing to the nonlinearity of the electrical properties of the crystal, by generation of electromagnetic waves with frequency ω_3 equal to frequency differential $\omega_1 - \omega_2$ of waves incident on the sample [14, 16–19]. Lasers based on a difference frequency of two CO_2 lasers emitting at $\lambda = 10.6$ and 10.3 μm upon mixing in GaAs reach 10^6–10^9 W in a picosecond pulse [14, 16–18].

One method of generating relatively high-energy (millijoule) pulses in the THz range is optical rectification of ultrashort optical laser pulses in nonlinear crystals, which occurs when an intense nonlinearly polarized laser pulse mimicking the shape of the optical pulse envelope is transmitted through the crystal [2]. The arising current spike can be an effective source of THz radiation.

Relatively high-energy THz laser radiation is also obtained by generation in a free-electron laser. The Novosibirsk free-electron laser emits up to 400 W in the short-wavelength THz range ($\lambda \approx 120$–240 μm; the pulse duration τ is about 100 ps; and the pulse repetition frequency is $f = 5.6$ MHz) [20].

High-quality optical materials capable of operating efficiently under such radiation exposure are required to deal with such radiation. It should be taken into account that the interaction of radiation with optical materials in the THz region differs from interaction in the traditional visible and IR ranges [5, 21, 22]. The present study analyzes the properties of optical materials usable in the THz range.

1. CRYSTALS

Crystals, such as silica, crystalline quartz, and sapphire are normally used for the THz optics [23]. Polycrystalline diamond (PD) is used in powerful THz sources, the use of which can overcome, at least partially, a backlog in the application of the THz range in comparison with the other traditionally used ranges of electromagnetic radiation [24, 25].

Radiation losses in crystals occur for two main reasons. These are the absorption on the lattice oscillations (phonon absorption) and the absorption on free charge carriers. The structure of diamond, in which germanium and silicon also crystallize, is considered to be the best lattice for THz crystals. The concentration of free charge carriers generally can be evaluated by the value of bandgap ΔE_g. However, it should be taken into account that the absorption cross-section of carriers in different materials can differ markedly. Nevertheless, it is clear why diamond with ΔE_g = 5.5 eV is the best THz crystal [25]. But since diamonds—even polycrystalline ones—are still significantly more expensive than other THz crystals, they are used only in powerful sources.

A significant loss from Fresnel reflection, caused by a large value of the refractive index, is a problem in the application of THz-range crystal optics. Due to the large wavelengths, the traditional methods for applying an antireflection coating to optics are ineffective in the THz region. Company Tydex offers the application of a parylene coating [23]. The technology

Table 1. Main physical properties of crystals [9, 23–25, 34, 40–46]

Crystal	Ge	Si	SiC	Crystal quartz	Sapphire	Diamond
Refractive index (λ = 10.6 μm)	4.0	3.4	3.12	n_0 = 1.535 n_e = 1.544 (λ = 1.0 μm)	1.75 (λ = 1.06 μm)	2.38
Density, g/cm^3	5.33	2.33	3.21	2.65	3.97	3.51
Harness (Mohs scale)	6.0	7.0	9.5	7.0	9.0	10
Melting point, °C	936	1412	2830	1470	2040	700*
Young's modulus (GPa)	138	189	392	97.2 (∥ to Z axis)	335	883
Thermal conductivity (300 K, W m^{-1} K^{-1})	59	152	490	10.7 (∥ to Z axis)	27.21	2000
Specific heat (J cm^{-3} K^{-1})	1.652	4.79	2.1	2.68	1.66	1.561
Coefficient of linear expansion (10^{-6} K^{-1})	5.75	2.33	4.5	8.0	5.6 (∥ to C axis)	1.0

*The temperature of conversion of diamond into graphite.

of applying parylene to flat surfaces is well known in microelectronics. By improving it, high-quality application of an antireflection coating to both flat and spherical optical surfaces was achieved. But the losses in precision silicon lenses designed for submillimeter astronomy applications were up to 6%, which proved to be too much [26].

In [26], other methods for obtaining an antireflection coating for the THz range on the surface of silicon are also analyzed. The methods of production of an antireflection layer by means of creating a diffraction pattern on the surface by the mechanical treatment, as well as creating thin etched layers of silicon by deep reactive ion etching for subsequent gluing with lenses are examined in detail. It is shown that the diffraction methods of producing an antireflection layer are more efficient and allow one to achieve a loss rate of less than 1% from reflection on each interface in the range from 0.787 to 0.908 THz. Physical effects arising upon creating periodic relief structures on the optical surface with a high degree of regularity and a period of less than the radiation wavelength are described in detail in monographs [27, 28]. This method also makes it possible to create planar lenses.

Diamond, germanium, and silicon are isotropic crystals, so their transmittance does not depend on the crystal orientation. Silicon carbide, crystalline quartz, and sapphire are anisotropic crystals, which should be taken into consideration when using.

Germanium and silicon are well processable, which allows one to fabricate high-precision optical components from them. However, since silicon is much more abundant in nature and significantly cheaper, articles made of germanium are used only in those cases when Ge has an apparent advantage over silicon. Silicon is a material for various systems operating in the intermediate IR range (3–5 μm), and germanium is used mainly in devices operating in atmospheric window 8–14 μm, because silicon shows significant phonon absorption in this area. Due to the high refractive index value and good physicochemical properties, germanium and, especially, silicon are widely used for manufacturing substrates of high-quality interference mirrors with a reflection coefficient of 99.5% and even higher, and narrowband interference filters for different regions of the IR spectral range. Items that are made of Ge and Si are convenient in operation, not interacting with atmospheric moisture, non-toxic, durable, and possess good thermophysical properties. Major physical properties of crystals for the THz range are given in Table 1.

1.1. High-Resistance Silicon Grown by the Floating-Zone Method (HRFZ-Si)

The most commonly used material in THz optics is high-resistance silicon grown by the floating-zone technique, since this is the most studied material that well transmits THz radiation. Silicon is one of the most technologically advanced materials that allow one to design on its base various optical components of rapidly developing THz electronics. Compared to other optical materials, it is cheaper for growing crystals and processing, and also has significantly larger sizes that allow one to diversify the range of manufactured optical components.

High-resistance silicon is the main isotropic crystalline material suitable for the use in an extremely wide range of wavelengths, from near-infrared (1.2 μm) to millimeter (1000 mm) or longer-wavelength ranges (Figs. 1 and 2). But this material can be used, in fact, in a much wider range of wavelengths.

High-resistance silicon shows relatively low losses in the THz range. As is seen from Fig. 3, the shapes of

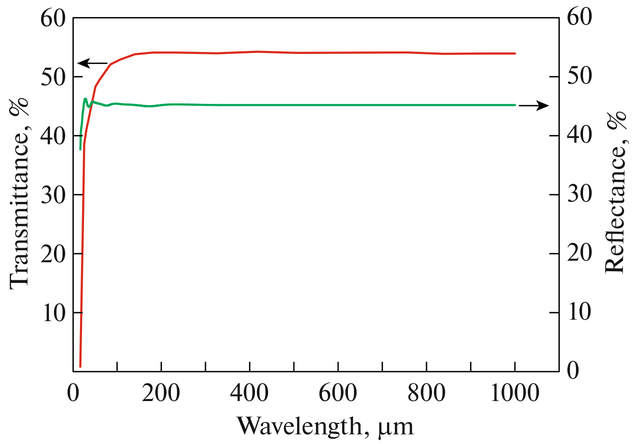

Fig. 1. (Color online) Transmission and reflection of high-resistance silicon with a thickness of 1 mm in the THz range [29].

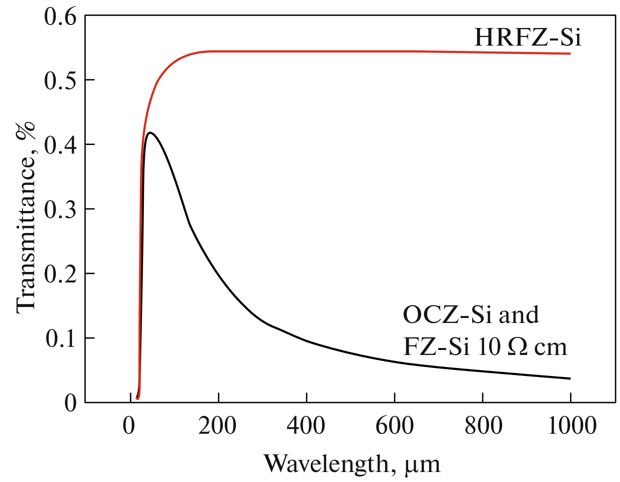

Fig. 2. (Color online) Transmission of silicon in the range 16–1000 μm; the thickness of samples is 5 mm [29].

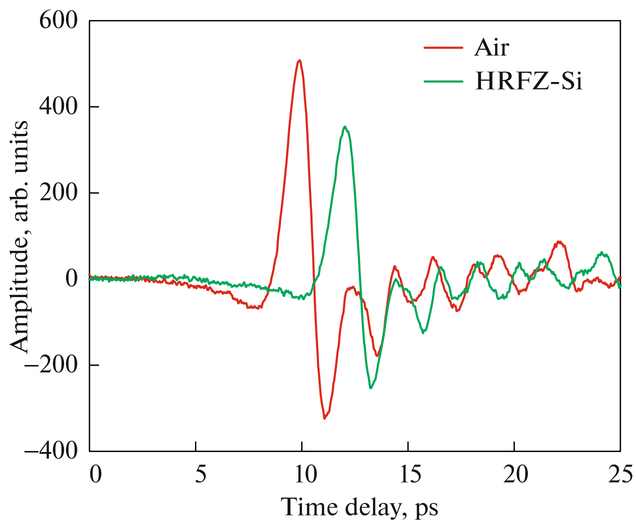

Fig. 3. (Color online) THz signals passed through the air and high-resistance silicon [23].

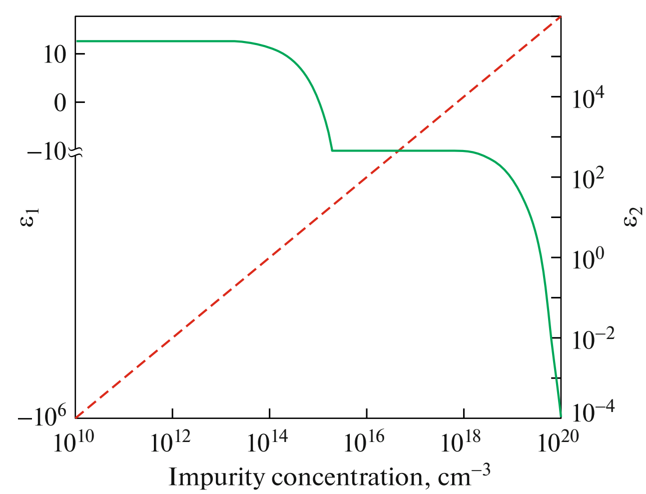

Fig. 4. (Color online) The real (ε_1, solid line) and imaginary (ε_2, dashed line) parts of the dielectric permittivity of silicon with different concentration of free carriers at a frequency of 1 THz [23].

the THz signals transmitted through the air and transmitted through high-resistance silicon are identical. This indicates the absence of significant absorption in silicon. Major transmission losses are largely caused by Fresnel reflection. The absorption coefficient of high-resistance silicon in terahertz range 0.25–2 THz is less than 0.5 cm^{-1}.

High-resistance silicon grown by the floating-zone method, which provides 50–54% transmittance in the range of wavelengths from 50 to 1000 μm (and longer, up to 8000 μm), is commonly used for the far-infrared and THz regions. Normally, this kind of silicon has a resistivity of about 10 kΩ cm [2, 3, 29, 30]; the preparation of silicon with a resistivity up to 50 kΩ cm is reported in [31, 32]. In [30, 32], record-low losses are reported in silicon compensated by gold; thus, losses in the millimeter range for the best samples were recorded at a level of $\tan\delta \approx 3 \times 10^{-6}$.

Complex dielectric permittivity of silicon depends on its conductivity, i.e., on the concentration of free carriers. A dependence of the dielectric permittivity of silicon on the concentration of impurities ($f = 1$ THz) is given in Fig. 4. If concentration of free carriers is low, then the dielectric permittivity is a real value and is equivalent to the high-frequency permittivity.

With an increase in the concentration of free carriers, the real part of the dielectric constant becomes negative, and its imaginary part ceases to be negligible. On account of this, the losses in silicon in the THz range increase. The dielectric loss tangent can be cal-

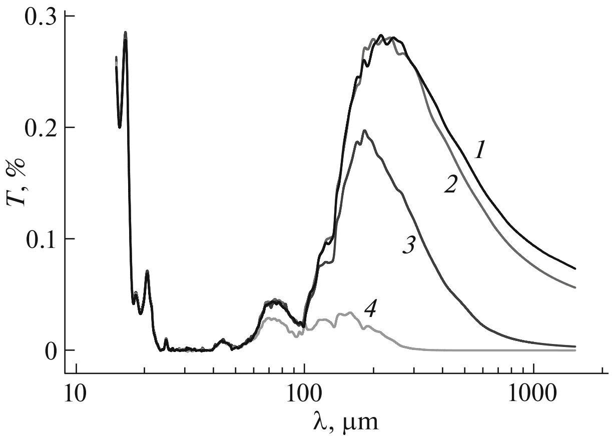

Fig. 5. Optical transmission of single crystals of (*1*) undoped germanium and (*2–4*) germanium doped with antimony; the resistivity values are as follows: (*2*) 46, (*3*) 20, and (*4*) 5 Om cm [39].

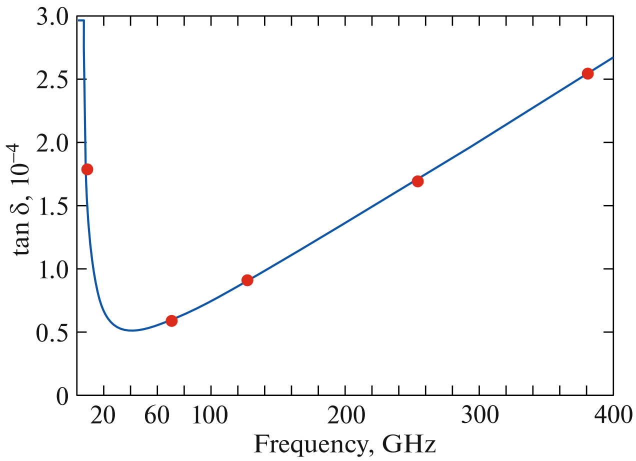

Fig. 6. (Color online) Frequency dependence of the tanδ value for the crystal of polytype 6H-SiC [41].

culated using the following formula: $\tan\delta = 1/(\omega\varepsilon_v\varepsilon_0 R)$, where ω is the angular frequency, ε_v is the dielectric constant of vacuum (8.85×10^{-12} F/m), ε_0 is the dielectric permittivity of silicon (11.67), and R is the resistivity. For example, the dielectric loss tangent of high-resistance silicon with a resistivity of 10 kΩ cm at a frequency of 1 THz equals 1.54×10^{-5}.

1.2. Germanium (Ge)

Germanium is used in the infrared technologies [33–36] for the manufacture of optical instruments and devices for various purposes. These are articles in the form of protective windows, lenses, acoustooptical components (ground-based, sea-based, and air-based optical instruments, and equipment for spacecrafts). The main consumer of germanium in optics are manufacturers of thermal imaging cameras operating in wavelength range 8–14 μm, which are used in passive thermal imaging systems, infrared guidance systems, night vision devices, and fire protection systems. Germanium is also used for the manufacture of high-performance photovoltaic cells (solar panels) and in detectors of the ionizing radiation and infrared sensors. Monocrystalline germanium is normally used, but if the absorption losses are not significant and optics is not associated with the formation of images, then the cheaper polycrystalline material is used.

The use of germanium for manufacturing active components of acoustooptical devices operating in the THz range is of interest [37]. Germanium can also be used in multispectral thermal imaging devices operating in the infrared + THz ranges [33] and THz lasers pumped with a CO_2 laser.

Unlike the infrared range, in which a minimum absorption of about 0.02 cm^{-1} (for λ = 10.6 μm) is observed in the *n*-type crystals with a conductivity of 5–10 Ω cm, the minimum losses in the THz area are observed in the own crystals (undoped or ultrapure). With an increase in the wavelength, the losses increase because of the absorption on free carriers (Fig. 5) [35, 37–39]. The attenuation coefficient of Ge in the range 160–220 μm is about 0.5 cm^{-1}, which is comparable to Si [39]. Based on the measurements performed using a free-electron laser, the attenuation coefficients of germanium at a wavelength of 140 μm are recorded in the range 0.75–1.04 cm^{-1} [37, 38].

1.3. Silicon Carbide (SiC)

Silicon carbide is a relatively new THz material, but its use is impeded by the inaccessibility of high-quality monocrystalline samples. This is a high-bandgap semiconductor that has more than 200 polytypes, but only three of them with a maximum width of the forbidden zone have real future in THz technological applications. The most interesting materials are 3H-SiC and 6H-SiC with a forbidden zone widths of 2.36 and 3.03 eV, respectively [40–42].

The main application area of SiC in the THz region is the production of energy input/output windows operating at a power level of 50–500 kW [40–42]. This material is slightly inferior to diamond, but diamond is considerably more expensive yet.

In [40–42], dielectric losses in monocrystalline silicon carbide of the 6H-SiC polytype was investigated in the frequency range from 6 to 380 GHz (Fig. 6) and the temperature range from 20 to 550°C. At low frequencies ($f < 10$ GHz), the dielectric loss tangent is about $1/f$. At $f > 50$ GHz, the losses increase with an increase in the frequency. In the low-temperature range ($T = 20$–250°C), the loss tangent quasilinearly increases with an increase in the temperature (Fig. 7). At $T > 300$°C, the losses grow exponentially.

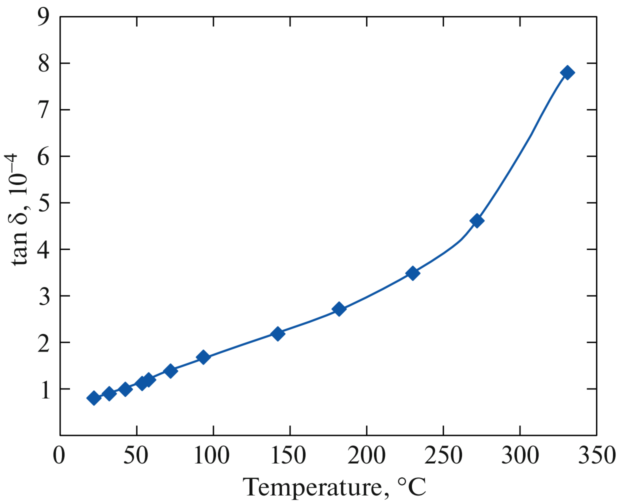

Fig. 7. (Color online) Temperature dependence of the tanδ value in the temperature range 20–350°C [41].

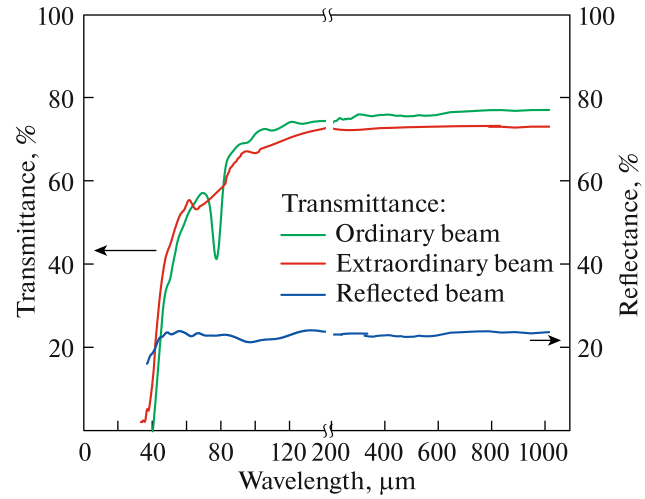

Fig. 8. (Color online) Transmission of a crystalline quartz sample with a thickness of 1 mm [44].

1.4. Crystalline Quartz

The range of optical transparency of crystalline quartz in the visible and near-infrared regions of the spectrum is quite broad and determined by the wavelength range 0.15–4 μm. The good transmittance of the material, starting from 100 μm, allows one to use it in the THz range as well.

Synthetic crystalline quartz is grown in autoclaves by the method of hydrothermal synthesis on preliminarily prepared and specially oriented nucleating plates (seeds) [43, 44]. The growth cycle continues a few months under a strictly maintained and around-the-clock controlled temperature of about 400°C and a pressure of up to 1000 bar. The orientation of seeds determines the location of the crystallographic axes of the grown crystal.

Crystalline quartz is an anisotropic uniaxial crystal with the trigonal structure. The crystal structure is of a framework type and built of silicon–oxygen tetrahedrons arranged helically (with the right-handed or left-handed helices) in relation to the main axis of the crystal. Depending on this, right and left structural-morphological forms of quartz crystals are distinguished. The absence of the planes and center of symmetry determines the piezoelectric and pyroelectric properties displayed by crystalline quartz. The material exhibits pronounced birefringence and high bulk homogeneity of the refractive index. The transmission of a 1 mm thick quartz crystal in the THz range is shown in Fig. 8.

Crystalline quartz is widely used in radio engineering, electronics, optoelectronics, and instrument engineering to create high-precision optical components for laser, polarization, and spectral optics, because of the following characteristic properties: (i) high optical homogeneity and internal crystallographic perfection; (ii) relatively high hardness, which itself imparts good processability to the material and wear resistance to operating surfaces during the exploitation; (iii) high chemical resistance to the influence of the environment; (iv) insolubility in water and other solvents; (v) a low thermal expansion coefficient; (vi) good dielectric characteristics, including those in broad frequency and temperature ranges and in strong electric fields; (vii) a wide range of optical transmission; (viii) resistance to the influence of high-power laser radiation (including UV radiation).

It should be mentioned separately that the above properties, together with the high optical transmission in the UV range, make crystalline quartz a unique material for the creation of optical components for a whole range of instruments, devices, and complex systems operating in the UV range.

Windows made of this kind of quartz exhibit important properties, such as: the transparency in the visible wavelength range, which makes it easy to align an optical system by using a helium–neon laser; they do not modify the state of linear polarization of a beam; and they may be cooled below the lambda point of liquid helium.

Due to rather large dispersion, lenses made of crystalline quartz will have different focal lengths in the visible and THz ranges. This should be taken into account when adjusting the optical systems with such lenses.

Since the crystalline quartz is a birefringent material, this fact should be taken into account when the polarization of radiation is an important factor. The *X*-cut material is used in the production of λ/2 and λ/4 waveplates for operating with *T*-waves.

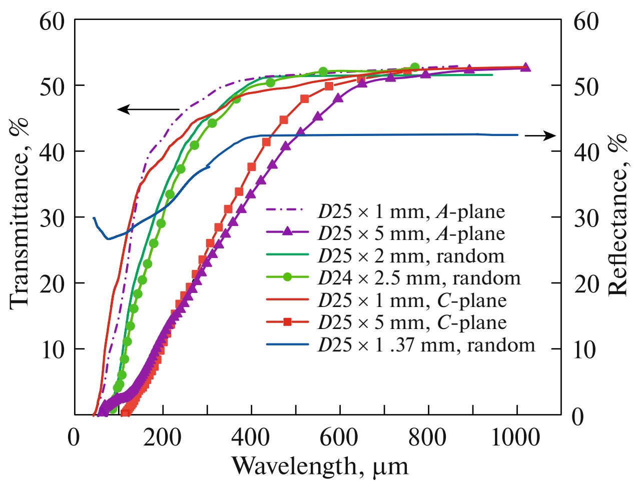

Fig. 9. (Color online) Transmission of sapphire samples of different thicknesses and crystallographic orientation [46].

1.5. Sapphire (Al_2O_3)

Sapphire (corundum) is widely used in optics and in electronic, optoelectronic, and laser technologies [45, 46]. It is an anisotropic uniaxial crystal. This is one of the most solid and durable synthetic materials. It shows chemical inertness and a low coefficient of friction. The wear resistance of corundum is 8 times higher than that of steel. Being a dielectric and thermally stable material up to 1600°C, sapphire also shows excellent optical properties, in particular, the optical transparency in the ultraviolet, visible, and infrared regions in the range from 0.17 to 5.5 μm. Sapphire is transparent in the THz region as well (Fig. 9). One can see that the optical transmission of sapphire does not depend on the crystal orientation within the specified accuracy of measurements. For measured samples with a thickness from 1 to 5 mm, the transmission below 600 μm strongly depends on the thickness of the sample. The transmission for thinner samples approaches to saturation at shorter wavelengths.

The above listed features of sapphire make this material indispensable for operation under harsh conditions, such as high temperatures and/or pressures, in acid or alkaline environments when chemical resistance is required, and also at high mechanical loads. Even under such severe conditions, sapphire does not lose its optical properties.

Akin to high-resistance silicon, sapphire is used in the production of photoconductive antennas operating in the THz range.

1.6. Polycrystalline Diamond

Diamond is a crystal has been known since ancient times [24, 25] but started to be used in technological applications relatively recently. Attempts to use diamonds in various technical devices were made a long time ago, but natural diamonds are too expensive and small in size, and have a significant discrepancy of parameters because of differences in their process of growth under natural conditions. The unique properties of diamond are determined by its crystalline structure—due to the lowest possible interatomic distance, diamond has an extremely high value of the crystal lattice energy.

The stable crystalline structure for carbon atoms is a hexagonal structure and this modification is known as graphite. Crystallization of carbon into the cubic diamond structure in nature occurs at very high temperatures (≥2000°C) and pressures (≥15 GPa). In the middle of the 20th century, an industrial technology for the preparation of synthetic diamond single crystals was created, which reproduces the natural conditions. These crystals have found so many applications in different branches of engineering, that "the economic potential of the most developed states largely became associated with the use of diamonds in them." Unfortunately, the technology is so technically complex that obtaining crystals over 8 carats (about 1.6 g) is not cost-effective.

In 1956, Spitsyn and Deryagin offered a fundamentally new, technologically and ecologically viable, technology for the synthesis of diamonds, namely, plasma chemical vapor deposition at pressures of less than 1 atm. This process is often referred to as the CVD technology. The raw materials, i.e., methane and hydrogen, are readily accessible [25, 47]. At the present, plates of polycrystalline diamond (PD) with a diameter of up to 300 mm have already been obtained. Basic technical characteristics of PD correspond to the properties of natural diamonds and, unlike the latter, they are technologically reproducible. As later transpired, this method allows one to prepare even relatively large single crystals of gem quality [48].

Diamond is a construction material for power optics and electronics, which combines astonishing physicochemical properties. Being transparent in the range from the ultraviolet to the millimeter ranges (except for the region of phonon absorption at 2–6 μm) (Fig. 10), it shows the unique thermal conductivity, which is 5 times higher than that of copper, and a low thermal expansion coefficient comparable to that for invar. These properties allow diamond to withstand radiation exposures that are noticeably larger than the exposures that other materials can withstand (5–10 MW/cm^2 at λ = 1.07 μm) [24, 49, 50]. For the application in relatively low-powered sources, polymer materials are typically used, but they cannot be used in powerful emitters. Namely, PD is a sole material used in the input/ouput windows of powerful electrovacuum and gas-discharge radiation sources. A ∅40 mm PD window with is used in the Novosibirsk free-electron laser having an average power of 400 W [20].

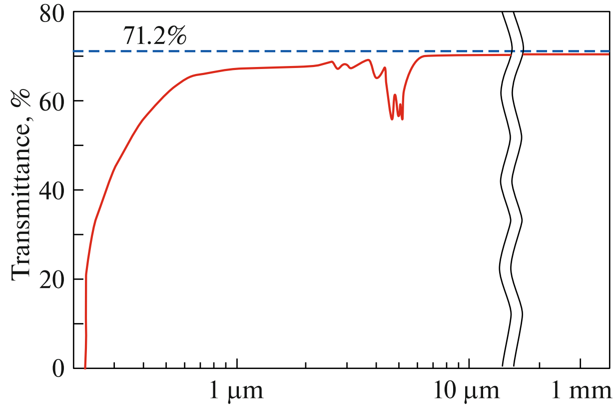

Fig. 10. (Color online) Transmission spectrum of a 1 mm thick PD plate [25].

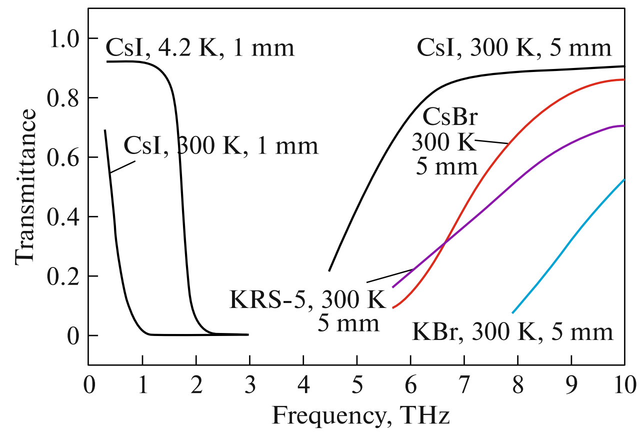

Fig. 11. (Color online) Optical transmission of halides at temperatures of 4.1 and 300 K [2].

Gyrotrons are widely used as high-power electromagnetic radiation emitters of the millimeter range [25, 50]. The output window between the operating area of the device and atmosphere is an integral part of their design, which forced to pay considerable attention to the study of optical materials transparent in this range during the development of gyrotrons. As it turned out [25, 50], diamond has minimal losses in this region. The loss tangent (at a frequency of ν = 170 GHz) is $\tan\delta = 10^{-5}$, which corresponds to an absorption coefficient of about 10^{-3} cm^{-1}, and this value is three to four orders of magnitude lower than the theoretical value [51]. The record-breaking thermal conductivity of diamond, which is about 2000 W/m grad, allows one to cool the window at megawatt exposure levels [25, 50]. In gyrotrons with an average power of about 1 MW ($\lambda \approx 3$ mm), ∅100 mm PD windows with a thickness of 1.2 mm are used.

1.7. Cesium Iodide (CsI) and Thallium Bromoiodide (KRS-5)

Instruments operating in the range 2.5–50 μm are commonly used in IR spectroscopy. Dielectric crystals CsI and KRS-5 are used in them, since only these crystals are transparent in the range 30–50 μm. The industry produces large-sized single crystals of TlBr–TlI (KRS-5) solid solutions and CsI crystals. Due to the high plasticity and low hardness, these crystals are very complicated in use.

CsI crystals are characterized by low hardness, high hygroscopicity, and poor thermophysical properties. They are fairly plastic. The industry produces large CsI crystals for optics operating in the far-IR range and for the production of scintillation detectors for high-energy particles.

KRS-5 is mainly identical to CsI by its physicochemical properties, but is more often used in optics because of somewhat better mechanical and climatic properties. Owing to the relatively high photoelastic constants, crystals of KRS-5 are used in the manufacture of acoustooptical components. Their use is limited by high toxicity, plasticity, and poor mechanical and thermophysical properties.

These crystals are transparent in the THz region (Fig. 11). Their advantage is a low refractive index (n = 1.74 for CsI and n = 2.35 for KRS-5; the data are given for λ = 10.6 μm) and, consequently, high optical transmission. However, it is necessary to use much thicker parts because of low mechanical characteristics.

2. POLYMERS

Among the large variety of polymers, there are some of them that show excellent transparency for THz waves. The low refractive index ($n \approx 1.4$–1.5) is a great advantage of polymers, owing to which they have significantly fewer losses from reflection, unlike the crystals. Polymethylpentene (TPX), polyethylene (PE), and polytetrafluoroethylene (PTFE or Teflon) are the best materials in this sense [23, 52].

Main physical properties of polymers are given in Table 2.

Table 2. Main properties of polymers [23, 52]

Material	TPX	Polyethylene	Teflon
Density, g/cm^3	0.83–1.08	0.91–0.925	2.2
Refractive index	1.46	1.54	1.43
Melting point, °C	235–240		327
Thermal stability, °C	–60–180	Up to 110	–73–204
Elastic modulus (at 23°C), MPa	690–1700	118–350	480–628
Tensile yield strength (at 23°C), MPa	14–25	8–13	14–30

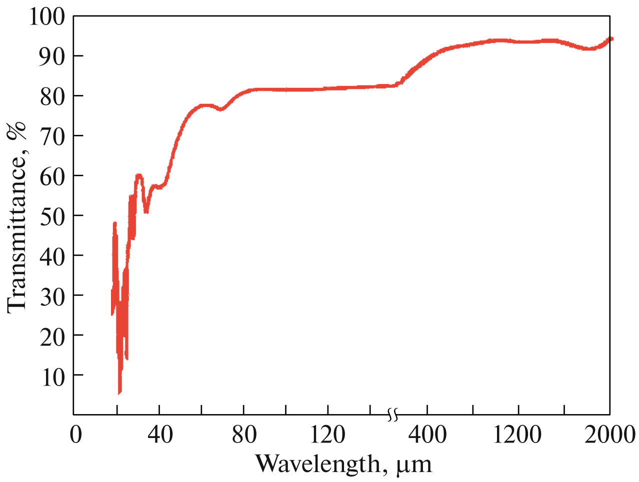

Fig. 12. (Color online) Transmission of a TPX window with a thickness of 2 mm in the THz range [23].

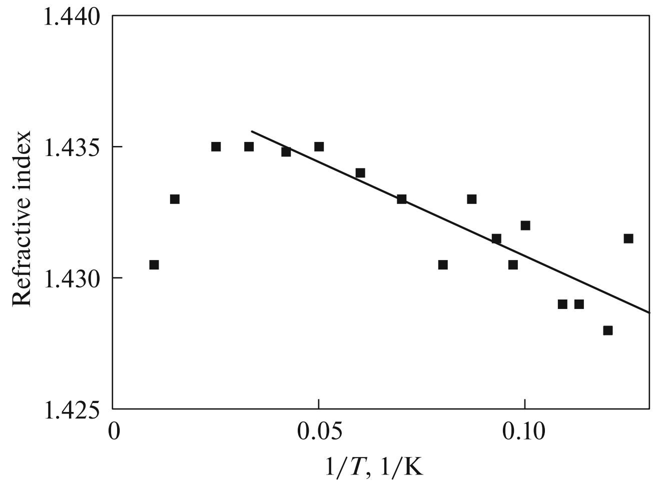

Fig. 13. Temperature dependence of the refractive index of TPX [23].

At large wavelengths, the optical transmission of these polymers weakly depends on the wavelength and the absorption bands are absent. At short wavelengths, characteristic absorption bands, for the most part below 200 μm, associated with their own vibrations are observed, as well as scattering on different kinds of inhomogeneities increases. In the range of shorter wavelengths, the transmission of radiation by polymers typically decreases, although TPX is the exception.

2.1. Polymethylpentene (TPX)

Polymethylpentene is a semicrystalline polymer with very good electrical insulating properties.

Polymethylpentene (more precisely, poly-4-methylpentene-1) is a crystallizing material with high transparency—its optical transmission reaches 94% and haze is from 0.7%. Unlike its closest "relative" polypropylene, whose transparency is achieved by reducing the sizes of crystal formations when adding a nucleator, polymethylpentene remains transparent even with larger sizes of crystallites. This is due to the fact that the density and refractive index of its amorphous and crystalline phases are very close. Polymethylpentene is a very lightweight material; TPX has the lowest density among all plastics. It has a very low water absorption rate and is dimensionally stable. It shows good resistance to alcohols and most organic and inorganic solvents, is water-resistant, and can be sterilized. TPX possesses good toughness, hardness, and impact strength. TPX is resistant to cracking and can be easily processed mechanically and polished. Most frequently, this material is recommended to use in the case when a combination of properties, such as the excellent transparency and good mechanical properties are imperative. It is mainly used in mechanical engineering, medical technologies, instrument engineering, including precision instrument engineering, electrical engineering, and food industry. It is widely used in the automotive industry, in the manufacture of household appliances, microwave technologies, and optical technologies. TPX exhibits good thermal stability, resistance to creep, and good resistance against gamma radiation and X-rays. TPX shows excellent heat resistance and resistance to most organic and inorganic commercial chemicals.

Optical properties of TPX are given in Figs. 12–14.

TPX is transparent in the ultraviolet, visible, and infrared ranges, which allows one, for example, to use a red laser beam for the alignment of optical systems. Optical losses in this material are very low even for millimeter waves. The refractive index of polymer practically does not depend on the wavelength.

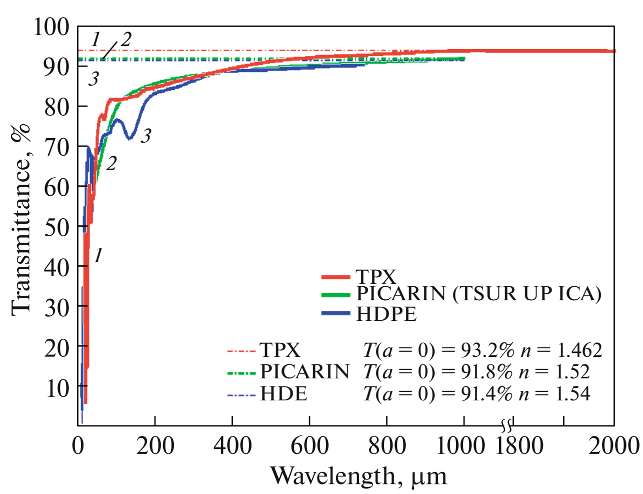

Fig. 14. (Color online) Transmission of samples of TPX, picarin, and HDPE (high density polyethylene) [23].

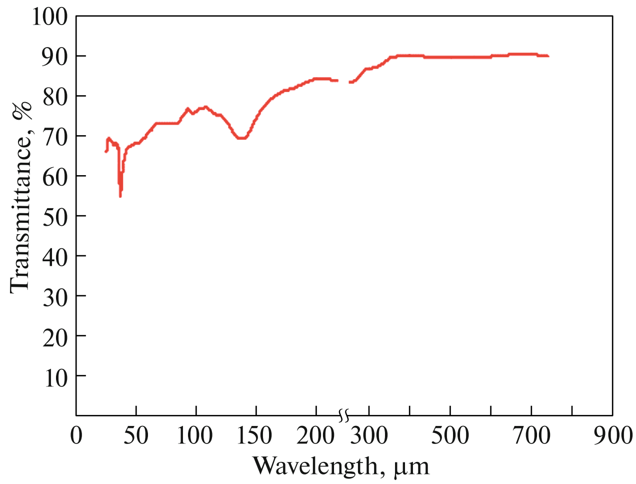

Fig. 15. (Color online) Transmission of a HDPE window with a thickness of 2 mm in the THz range [23].

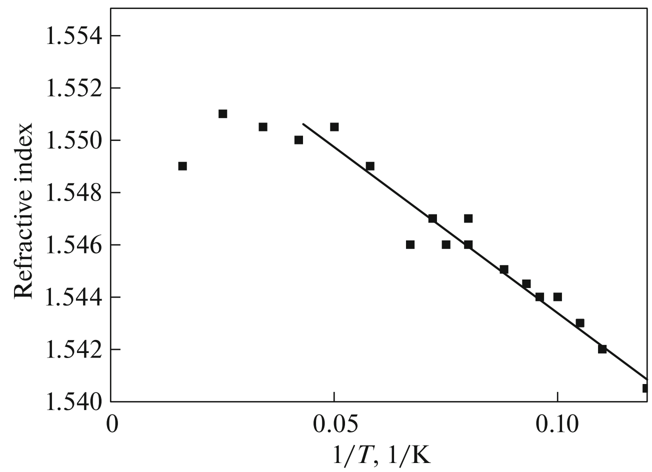

Fig. 16. Temperature dependence of the refractive index of HDPE [23].

TPX is a solid strong material that can be mechanically converted into various optical components such as lenses and windows. TPX can serve as windows in gas molecular lasers optically pumped by a CO_2 laser, on account of transparency in the entire THz range and absolute suppression of pumping radiation around 10 μm. TPX windows can also be used in cryostats as "cold" windows. The transmission of TPX in the THz range does not depend on temperature. The temperature coefficient of the refractive index of TPX is 3.0×10^{-4} K^{-1} (for the temperature range 8–120 K).

Compared to other materials used for the operation in the THz range, TPX exhibits excellent optical properties and can serve as a good replacement for the new THz material known as picarin (tsurupica) in the manufacture of lenses. The latter is commercially less accessible and substantially more expensive.

2.2. Polyethylene (PE)

Polyethylene is used in the production of films and various film items, such as the thermoplastic films and the packages. Food wrap PE has excellent dielectric characteristics. One of its advantages is chemical resistance, except for fats and oils, which dissolve PE. Externally, it is an almost completely transparent and weakly plastic material, which is an excellent electrical insulator, frost-resistant, not vulnerable to radiation, moisture-resistant, and gas-tight. Items made of PE are used in electrical engineering, chemical and food industry, automotive industry, construction, etc.

The refractive index of PE weakly varies in a wide range of wavelengths. Optical properties of PE are given in Figs. 15 and 16. Typically, high-density polyethylene (HDPE) is used for the production of optical components. Thin films of HDPE used in THz polarizers. HDPE is also used in the production of windows for the Golay cells.

Unfortunately, the transmission of HDPE in the visible range is very low, so one needs to use IR radiation to adjust the optical systems.

It should be noted that the transmission of HDPE in the THz range does not depend on the temperature, which allows one to use the material in cryostats. The temperature coefficient of the refractive index of HDPE is 6.2×10^{-4} K^{-1} (for the temperature range 8–120 K).

2.3. Polytetrafluoroethylene (PTFE, Teflon, Fluoroplast)

Polytetrafluoroethylene is a white, hard, and heavy plastic. Optical properties of Teflon are given in Fig. 17. PTFE is a white—transparent in a thin layer—substance resembling paraffin wax or polyethylene in appearance. It possesses high heat resistance and frost

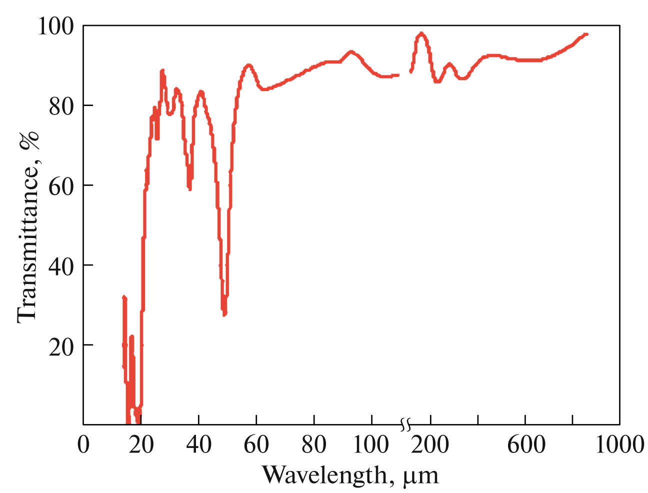

Fig. 17. (Color online) Transmission of a PTFE film with a thickness of about 0.1 mm in the THz range [23]

resistance and is an excellent insulation material. Teflon has a very low surface tension and adhesion and is moistened with neither water nor fat, nor the majority of organic solvents.

PTFE is an electrical insulator, excellent antifriction material, and fairly heat-resistant polymer, which enables its use in friction units without additional lubrication. Teflon is also used to make gaskets and washers, and joined components are never seized up. Parts made of Teflon are glued only if the surfaces are treated with special compositions, but even in that case the adhesion quality is not very high.

CONCLUSIONS

The selected organic materials, i.e., TPX, PE, and PTFE, demonstrate homogeneous and stable transmission of approximately 80–90% in the range starting from about 200 μm and extending up to 1000–2000 μm. Indeed, they also superbly transmit at higher wavelengths as well. However, the optical resistance of polymeric materials is usually lower than that of crystals.

Crystalline materials, such as silicon, germanium, quartz, and sapphire have lower transmittance values in the THz range because of losses from reflection. For samples that are 1–2 mm in thickness, these values are as follows: 35–40% for germanium (in the range 80–300 μm); 70–71% for diamond; 50–54% for silicon, starting from 50 μm; more than 70% for quartz, starting from about 120 μm; and more than 50% for sapphire, starting from about 350 μm. Moreover, the absorption coefficient in these materials (except for diamond) is at a level of $\alpha \approx 0.5\ \text{cm}^{-1}$. The absorption coefficient in diamond is $\alpha \approx 10^{-3}\ \text{cm}^{-1}$, which is three to four orders of magnitudes higher than the theoretical limit.

The above materials possess a significant, in terms of laser technology, absorption of about $0.5\ \text{cm}^{-1}$ or higher, which limits their use in high-power laser systems. In low-power systems, they can be used in the form of thin plates or films. However, interference effects must be taken into account in this case, since the thickness of the optical element can be comparable with the wavelength.

All instruments can be practically divided into two groups according to the output radiation energy (less than a millijoule or more than a millijoule). For the first group of emitters, it is possible to use not just crystals, but also polymers. For more powerful emitters, it is recommended to use crystalline materials.

The application of crystalline materials with high refractive indices is complicated by significant Fresnel reflection. Its reduction by applying interference coatings, which is traditionally used in optics, is nearly inapplicable in the THz range, because layers with thicknesses that are multiples of $\lambda/4$ are necessary in order to apply an antireflection coating, which is technologically possible only in the case of deposition of organic film materials that are not yet widely used. However, it is possible to apply an antireflection coating for the THz region by creating periodic surface relief structures with a high degree of regularity and a period smaller than the radiation wavelength. In this case, a long wavelength significantly reduces technological fabrication problems.

A relatively new optical material, polycrystalline diamond, has recently become available. This material shows good optical properties and is irreplaceable for powerful sources operating in the THz range [24, 25, 50]. In the THz range, two types of powerful radiation sources using a diamond window are currently known. In a short-wavelength part of the range, this is a free-electron laser, which emits frequency-pulse radiation with an average power of 400 W at wavelengths of 120–240 μm; in a long-wavelength part of the THz range, this is the gyrotron [20, 50]. These two very different devices have one thing in common: the radiation exits from them through a diamond window. Power diamond optical components can be used in nonlinear optical devices operating via isolation of a wave with a difference frequency. Silicon carbide can be recommended for use in less powerful sources.

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