

Terahertz (THz) radiation is located in the spectral region  $\sim 0.1\text{-}10\text{ THz}$  ( $\sim 3\text{ mm} - 30\text{ }\mu\text{m}$ ,  $3\text{ cm}^{-1} - 300\text{ cm}^{-1}$ ) between the microwave and mid infrared range of the electromagnetic spectrum.

In comparison with visible or infrared waves, THz radiation can penetrate into organic materials such as skin, plastics, cloth, or paper products. Because of low photon energy involved, it does not cause any damage associated with ionizing radiation (e.g. X-rays). THz waves do not penetrate into metals. These properties can be used in process (e.g. drugs manufacturing) and quality control as well as in THz imaging. It is also of great current interest for such applications as safety control, packaging inspection, semiconductor characterization, chemical composition analysis, and biomedical investigations, with great promise for spectroscopy, defense imaging, and security applications.

Traditionally for THz applications we use High Resistivity Float Zone Silicon (HRFZ-Si) as it is the most investigated substance for operating within this range and has a good transmission performance. In parallel with this material we have been investigating other materials which also can be utilized in THz range.

Below you can see transmission spectra and other characteristics of materials we use for THz optics production. Measurements in THz region were made at ABB FTIR spectrometer Bomem DA3 and Bruker IFS 125HR (measure of inaccuracy is 2-3% below  $100\text{ }\mu\text{m}$  and 4-5% over  $100\text{ }\mu\text{m}$ ). Measurements in near infrared range were made at Perkin Elmer "Lambda-9" (measure of inaccuracy  $< 0.5\%$ ).

## 1. Crystals

The crystals such as silicon, crystal quartz, and sapphire are important for THz optics production.

### 1.1 High Resistivity Float Zone Silicon (HRFZ-Si)

Besides synthetic diamond high resistivity silicon is the only isotropic crystalline material suitable for the extremely wide range from NIR ( $1.2\text{ }\mu\text{m}$ ) to MM ( $1000\text{ }\mu\text{m}$ ) waves and more. In comparison with diamond it is rather cheaper to grow and machine. Moreover it may have considerably bigger dimensions that allows manufacturing the elements of fast-developing THz electronics based on that. For THz applications we offer High Resistivity Float Zone Silicon (HRFZ-Si) maintaining 50-54% transmission to  $1000\text{ }\mu\text{m}$  (and for longer wavelengths up to  $3000$  and even to  $8000$  microns).

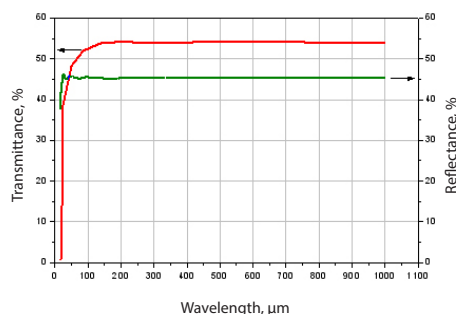


Fig.1 Transmission and reflection of HRFZ-Si 5.0 mm-thick sample in THz range

HRFZ-Si has low losses in THz range. As follows from Fig. 2 the THz waveform of HRFZ-Si is similar to the THz waveform of air. That indicates the lack of HRFZ-Si absorption.

The complex dielectric permittivity of silicon depends on its conductivity (i.e. free-carrier concentration). Figure 3 shows the dielectric permittivity of silicon at 1 THz with different impurity concentration. For low impurity concentration the dielectric permittivity is almost a real value, which is approximately equal to the high frequency dielectric permittivity. As a level of impurity concentration increases the real part of the dielectric constant becomes a negative value and its imaginary part can't be considered negligible anymore. The dielectric permittivity presents its complex nature and silicon becomes lost to THz wave.

Loss tangent can be calculated using the following formula:  $\tan\delta = 1/(\omega \cdot \epsilon_v \cdot \epsilon_0 \cdot R)$ , where  $\omega$  circular frequency,  $\epsilon_v$  -dielectric constant of vacuum ( $8.85 \cdot 10^{-12}\text{ F/m}$ ),  $\epsilon_0$  - dielectric constant of silicon (11.67), and  $R$  - specific resistance. For example, loss tangent of HRFZ-Si with resistivity  $10\text{ k}\Omega\text{cm}$  at 1 THz is  $1.54 \cdot 10^{-5}$ .

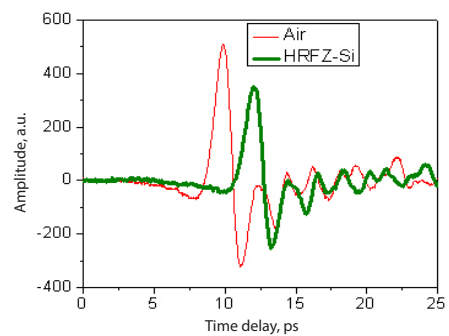


Fig.2 The THz signals transmitted through air and HRFZ-Si. (\*)

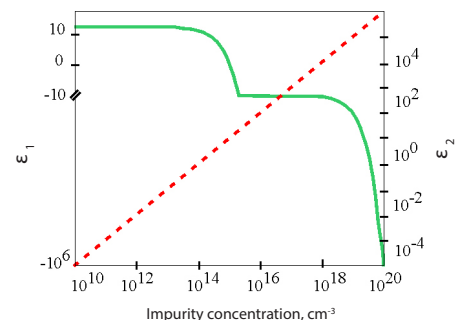


Fig. 3 Real (solid,  $\epsilon'$ ) and imaginary (dashed,  $\epsilon''$ ) part of dielectric permittivity of n-type silicon with different impurity concentration at 1 THz. (\*\*)

More about general characteristics of Silicon as well as transmission spectrum within NIR and MIR range can be found in the chapter Silicon.

### 1.2 Crystal Quartz

One of the best materials for wavelengths above  $50\text{ }\mu\text{m}$  is a z-cut crystal quartz.

The z-cut crystal quartz windows are transparent in the visible range that makes it easy to adjust the optical system by means of HeNe laser.

They do not change the state of light polarization and can be cooled down below the  $\lambda$ -point of liquid helium.

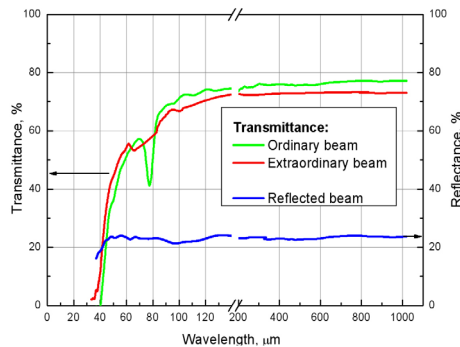


Fig. 4 Transmission and reflection of crystal quartz 1.0 mm-thick sample

Due to quite big dispersion (please see the table below) lenses made of crystal quartz will have different focal lengths at visible and far infrared ranges. It should be taken into account if you are using lenses for optical systems alignment:

$\lambda, \mu\text{m}$	$n_o$	$n_e$	$\lambda, \mu\text{m}$	$n_o$	$n_e$
0.589	1.544	1.553	100.0	2.132	2.176
6.0	1.32	1.33	200.0	2.117	2.159
10.0	2.663	2.571	333.0	2.113	2.156
30.0	2.5	2.959			

Crystal quartz is birefringent material that should be noted if the polarization of radiation is important. We use x-cut material to produce  $\lambda/2$  and  $\lambda/4$  waveplates for THz applications.

More about general properties of crystal quartz as well as transmission spectrum within UV and visible range you can find in the chapter Synthetic Crystal Quartz.

### 1.3 Sapphire

Sapphire like crystalline quartz is transparent in THz region as well as in visible one. Samples of various crystallographic orientations and thickness were measured. The transmission does not depend on crystal orientation within measure of inaccuracy.

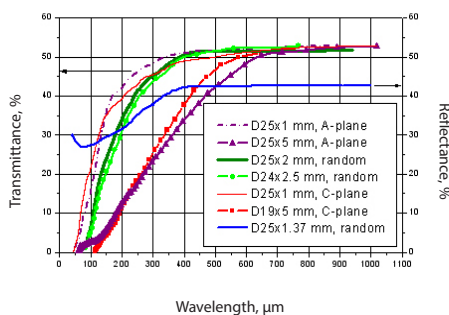


Fig. 5 Transmission and reflection of sapphire samples with different thickness

For measured samples with thicknesses from 1 to 5 mm transmission lower 600  $\mu\text{m}$  strongly depends on the sample thickness. The transmission approaches to saturation at shorter wavelengths for thinner samples.

Sapphire like HRFZ-Silicon also can be used for manufacturing of photoconductive antennas for THz because of similar refractive index value in THz.

More about general characteristics of sapphire and transmission spectrum within UV and visible range you can find the chapter Sapphire.

## 2. Polymers

Among large variety of available polymers there are some of excellent terahertz transparencies with relatively low reflectivity. The best materials are TPX (polymethylpentene), polyethylene (PE), and polytetrafluoroethylene (PTFE or Teflon). At longer wavelengths the transmission of these polymers is structureless and flat. Going to shorter wavelengths, mainly below 200  $\mu\text{m}$ , characteristic bands of intrinsic vibrations appear and scattering due to inhomogeneities increases. Polymers generally become increasingly opaque at shorter wavelengths.

### 2.1 Polymethylpentene (TPX)

TPX is the lightest of all known polymers. It is optically transparent in UV, visible, and THz ranges that for example allows using a HeNe laser beam for alignment. Index of refraction is  $\sim 1.46$  and is relatively independent on wavelength:

$\lambda, \mu\text{m}$	n	$\lambda, \mu\text{m}$	n
0.633	1.463	667	1.46
24	1.4568	1000	1.4650
60	1.4559	3191	1.466
300	1.46		

Losses are very low up to mm-wavelengths. TPX has excellent heat resistance and is highly resistant to most organic and inorganic commercial chemicals.

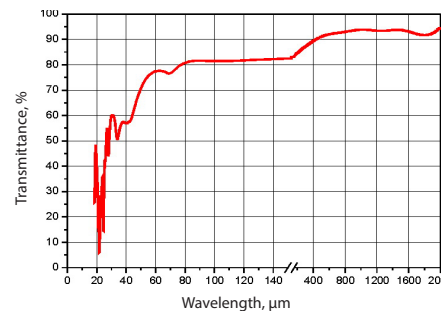


Fig. 6 Transmission of TPX 2 mm-thick sample. THz region

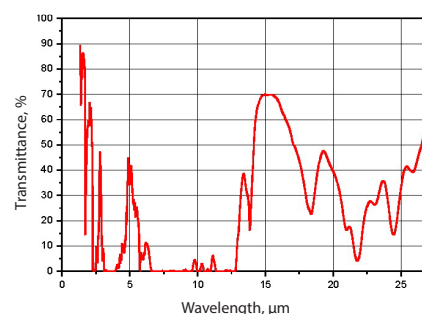


Fig. 7 Transmission of TPX 2 mm-thick sample. NIR&MIR regions

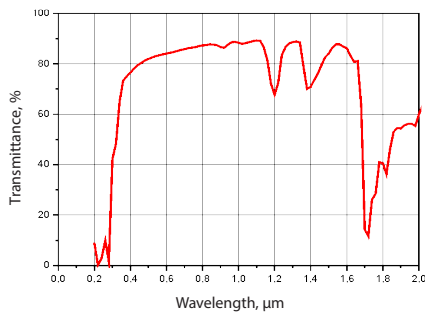


Fig.8 Transmission of TPX 2 mm-thick sample. UV&VIS&NIR regions

#### Typical properties of TPX

Density, g/cm <sup>3</sup>	0.83
Tensile strength	4100 psi (~28.3 MPa)
Tensile modulus	280000 psi (~1930.5 MPa)
Tensile elongation at break, %	10
Flexural strength	6100 psi (42.1 MPa)
Flexural modulus	210000 psi (1447.8 MPa)
Melting temperature, °F/°C	464 / 240
Water absorption (ASTM-D 1228), %	<0.01
Moisture permeability (thk 25 μm, 40C, 90%RH), g/m <sup>2</sup> *24h	110
Oxygen permeability (thk 100 μm), cm <sup>3</sup> /m <sup>2</sup> *d*MPa	120000

TPX is a hard solid material which can be mechanically shaped into various optical components (e.g. lenses and windows). Also specifically TPX is used in CO<sub>2</sub> laser pumped molecular lasers as output window because it is transparent in the whole terahertz range and totally suppresses the ~10 μm pump radiation.

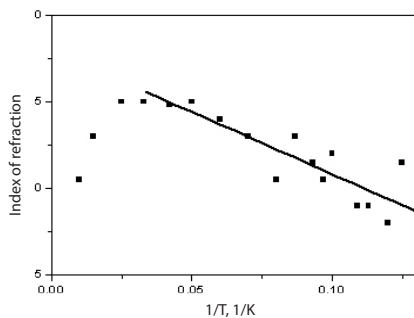


Fig. 9 Temperature dependence of refractive index(\*\*\*)

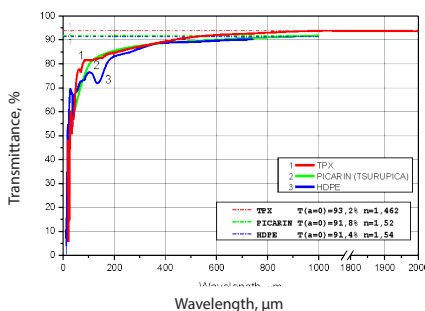


Fig.10 Transmission of 2 mm thick - samples of TPX, Picarin, and HDPE

In comparison with other materials, used for operating in THz range, TPX shows excellent optical properties and for example can be good substitution for Picarin (Tsurupica) lenses. In addition TPX is cheaper and commercially available in comparison with Picarin.

#### 2.2 Polyethylene (PE)

PE is a light elastic crystallizing material. It can be heated up to 110° C and cooled down to -45 ÷ -120° C depending on grade. PE has good dielectric characteristics, chemical resistance, and radioresistance. However it is unstable to UV-radiation, fats, and oils. PE is biologically inert and easy to be processed. Density (23°C) is 0.91-0.925 g/cm<sup>3</sup>. Tensile flow limit (23°C) is 8-13 MPa. Modulus of elasticity (23°C) is 118 - 350 MPa. Refractive index is ~1.54 and is rather equal within wide wavelength region.

Usually high-density polyethylene (HDPE) is used for component's production. Besides quite thick lenses and windows, thin HDPE films are used for THz polarizers. In addition we use HDPE as the window for Golay cells.

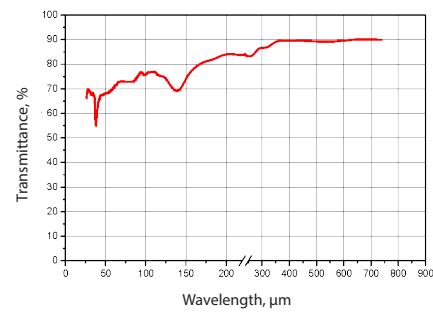


Fig.11 Transmission of 2 mm-thick HDPE sample. THz region

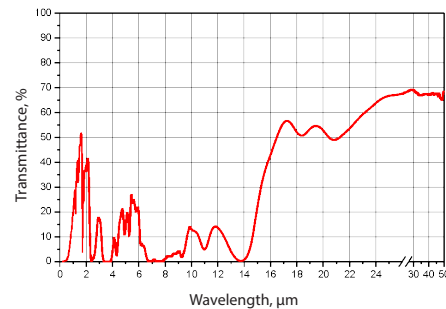


Fig.12 Transmission of 2 mm-thick HDPE sample. NIR&MIR regions

Unfortunately HDPE transmission in visible region is very poor, thus it can't be used for adjustment of optical systems. Should notice that THz transmission of HDPE doesn't depend on temperature that allows using HDPE windows in cryostats. Temperature coefficient of refractive index is  $6.2 \cdot 10^{-4} \text{ K}^{-1}$  (for the range 8-120 K).

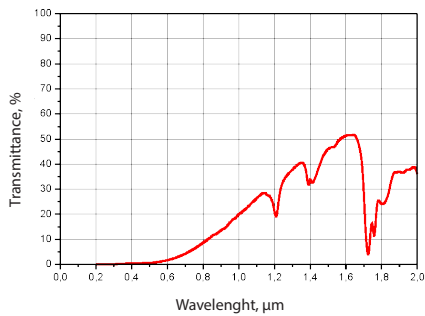


Fig.13 Transmission of 2 mm-thick HDPE sample . VIS&NIR regions

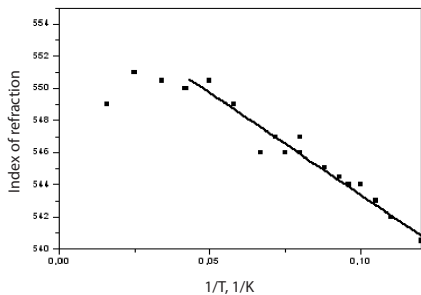


Fig.14 Temperature dependence of refractive index (\*\*\*)

### 2.3 Polytetrafluoroethylene (PTFE, Teflon, in Russian - Ftoroplast)

PTFE is a white solid at room temperature, with density of about 2.2 g/cm<sup>3</sup>. Its melting point is 327 °C, though its characteristics remain at the useful level over a wide temperature range of -73°C to 204°C. Refractive index is ~1.43 within wide wavelength region.

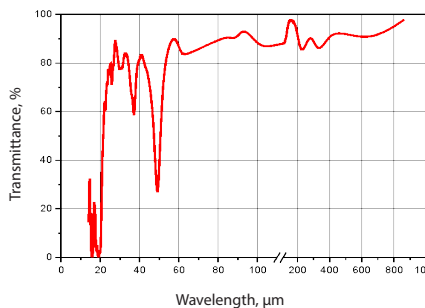


Fig.15 Transmission of PTFE film ~0.1 mm- thick. THz region

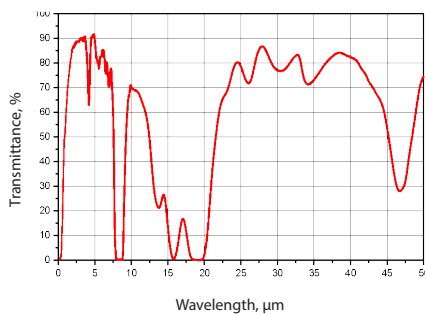


Fig.16 Transmission of PTFE film ~0.1 mm-thick. NIR&MIR regions

Due to good transmission in the range 1-7 μm PTFE films are used for manufacturing of IR polarizers. First cost of these polarizers is lower than for crystalline ones. It is advantageous for their mass application in IR sensors using polarized radiation.

#### Typical properties of PTFE

Tensile strength	3900 psi ~26.7 MPa
Tensile modulus (psi)	80000 psi ~551.6 MPa
Tensile elongation at break (%)	300
Flexural strength (psi)	No break
Flexural modulus (psi)	72000
Compressive strength (psi)	3500
Compressive modulus (psi)	70000

#### Summary

As you can see all organic materials like TPX, PE, and PTFE have uniform stable transmission about 80-90% starting from ~200 μm and up to 1000 μm. Surely they excellently transmit at larger wavelengths too.

Crystalline materials like silicon, quartz, and sapphire have lower transmission in THz range due to reflection losses. For silicon it is 50-54% starting from 50 μm, for quartz it is >70% starting from about 120 μm, for sapphire it is >50% starting from about 350 μm at 1-2 mm sample thickness. For price quotation and delivery please fax or e-mail us.

Also please pay attention we do not supply polymers and crystalline materials in blanks or as raw material. Our standard products are finished parts. Please learn more about Tydex THz components from the following chapters:

- THz Windows
- THz Lenses
- THz Prisms
- THz Mirrors
- THz Waveplates
- THz Spectral Splitters
- THz Beam Splitters

(\*) data are given by X.- C. Zhang and Jian Chen from Rensselaer Polytechnic Institute, USA.

(\*\*) X.- C. Zhang, J. Xu, Introduction to THz Wave Photonics, Springer Science+Business Media, LLC 2010 (p. 73).

(\*\*\*) data are given by J. Steven Dodge and Graham Lea from Simon Fraser University, Canada.