

Terahertz (THz) radiation occupies frequency range ~0.1-10 THz (~3 mm to 30  $\mu\text{m}$ ,  $3\text{ cm}^{-1}$  to  $300\text{ cm}^{-1}$ ) between microwave and far infrared spectral regions.

Unlike visible and infrared light, THz radiation can penetrate certain organic materials such as skin, plastics, textile and paper. Due to low photon energy, it doesn't cause damage associated with ionizing radiation (e. g. X-rays). THz radiation cannot penetrate metals. These features of the radiation can be utilized for in-situ production monitoring (for example, in pharmaceuticals), product quality control and THz imaging. It is also of great interest for other applications such as security control, packaging inspection, semiconductor characterization, chemical composition analysis and biochemical studies.

Traditional material for THz applications is the High Resistivity Float Zone Silicon (HRFZ-Si) as it is the most studied substance that is transparent in this range. Alongside this material, we have studied others that we considered promising for THz applications.

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

## 1. Crystals

Crystals such as silicon, crystal quartz, and sapphire play an important role for THz applications.

### 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 wavelength range, from NIR (1.2  $\mu\text{m}$ ) to millimeter (1000  $\mu\text{m}$ ) and more. Compared to diamond, it is much cheaper to grow and machine. Moreover, it may be produced in considerably larger dimensions, allowing production of wider variety of optical parts. Silicon is one of the most workable materials suitable for manufacture of components for the fast evolving field of terahertz photonics.

For THz components we use High Resistivity Float Zone Silicon maintaining 50-54% transmission between 50 and 1000  $\mu\text{m}$  (and for longer wavelengths up to 8000 microns).

HRFZ-Si has low losses in THz range. Fig. 2 shows that the waveform of a THz signal passing through air is identical to the waveform of signal passing through high-resistivity silicon. It indicates the lack of absorption in silicon.

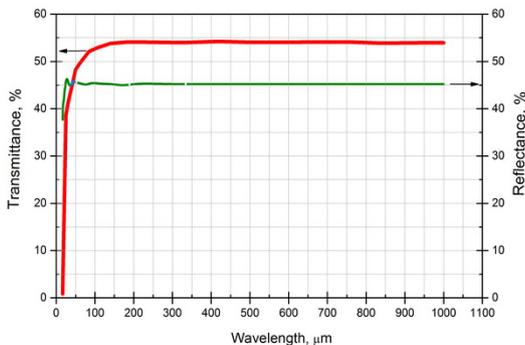


Fig. 1. Transmittance and reflectance of high-resistivity silicon. THz range.

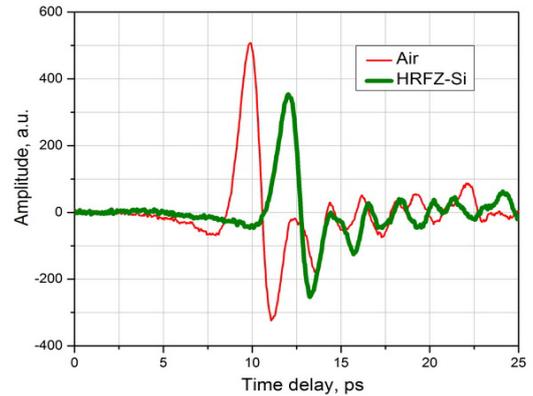


Fig. 2. THz signals passing through air and high-resistivity silicon (\*).

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 vs impurity content. For low impurity concentration the dielectric permittivity has a real value, and is equivalent to high frequency dielectric permittivity. As the impurity content grows, the real part of the dielectric constant becomes negative, and its imaginary part is no longer negligible.

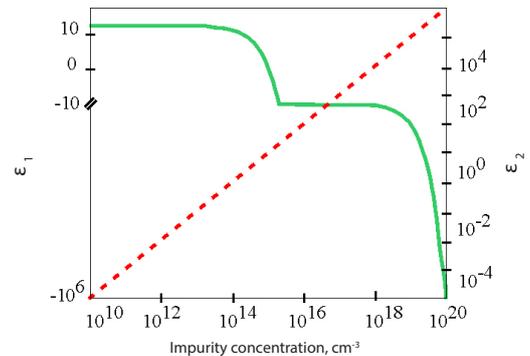


Fig. 3. Real (solid line,  $\epsilon_1$ ) and imaginary (dotted line,  $\epsilon_2$ ) parts of dielectric permittivity of silicon vs impurity content at 1 THz. (\*\*)

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

For more information about general properties of silicon, as well as transmission spectra in near and middle IR regions, refer to the chapter *Silicon*.

### 1.2 Crystal Quartz

One of the best materials for wavelengths above 50  $\mu\text{m}$  is a z-cut crystal quartz. The z-cut crystal quartz windows demonstrate the following important properties:

- They're transparent in the visible range, making it easy to adjust the optical system by means of HeNe laser;
- They do not affect linear polarization of the beam;
- They can be cooled below the  $\lambda$ -point of liquid helium.

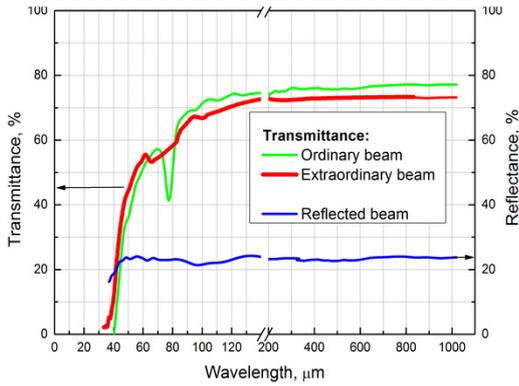


Fig. 4. Transmittance of 1 mm-thick crystal quartz sample.

Due to relatively high dispersion (see table below) crystal quartz lenses will have different focal lengths in visible and THz ranges. This should be taken into account if such lenses are used to adjust optical systems.

$\lambda, \mu\text{m}$	$n_o$	$n_e$	$\lambda, \mu\text{m}$	$n_o$	$n_e$
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. This must be considered if the polarization of light is critical for your application. We use x-cut material for  $\lambda/2$  and  $\lambda/4$  waveplates operating at THz frequencies.

For more information about general properties of crystal quartz, as well as transmission spectra in UV and visible regions, refer to the chapter *Synthetic Crystal Quartz*.

Thin fused silica elements also transmit long-wavelength radiation. Above 500-700  $\mu\text{m}$  the transmittance is the same as that of the crystalline material. In millimeter-wave applications, thin fused silica parts can be used to save costs.

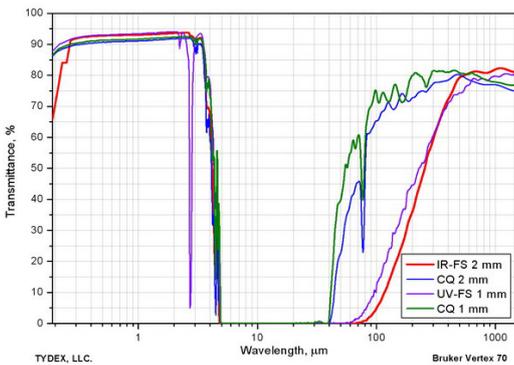


Fig. 5. Transmittance of crystal quartz windows KI and KU-1 of various thicknesses.

### 1.3 Sapphire

Like crystal quartz, sapphire is transparent both in submillimeter and visible ranges. As it is clear from the spectra below, sapphire transmittance does not depend on its crystal orientation. For measured samples 1 to 55 mm thick, transmittance below 600  $\mu\text{m}$  is highly dependent on sample thickness. For thinner samples, transmittance approaches saturation at shorter wavelengths. Similar to high-resistivity silicon, sapphire with its comparable refractive index can be used for hyper hemispheric lenses for THz detectors and

generators based on photoconductive antennas.

For more information about general properties of sapphire, as well as transmission spectra in UV and visible regions, refer to the chapter *Sapphire optics* on our website.

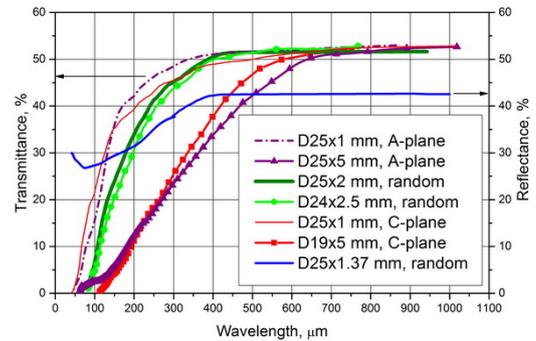


Fig. 6. Transmittance of sapphire samples of various different thicknesses and crystal orientations

## 2. Polymers

Among wide variety of polymers, there are some of excellent terahertz transparency with relatively low reflectivity. The best materials in this regard include polymethylpentene (TPX), Picarin (Tsurupica), cyclic olefin polymer (Zeonex), cyclic olefin copolymer (COC), polyethylene (PE), and polytetrafluoroethylene (PTFE or Teflon). At 200  $\mu\text{m}$  and above, transmittance of these polymers is over 80% and independent of wavelength. Below that, characteristic absorption bands appear due to natural oscillations. Scattering on various inhomogeneities also increases. TPX, Tsurupica, Zeonex and COC are transparent in visible range.

### 2.1 Polymethylpentene (TPX)

TPX is the lightest of all polymers. It is transparent in UV and far IR, as well as visible range, allowing optical systems to be adjusted using a HeNe laser beam. Its refractive index is  $\sim 1.46$  with almost no dispersion.

$\lambda, \mu\text{m}$	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		

Optical losses in the material are very low up to millimeter wavelengths. TPX has excellent heat resistance and is highly resistant to most commercially available chemicals, both organic and inorganic.

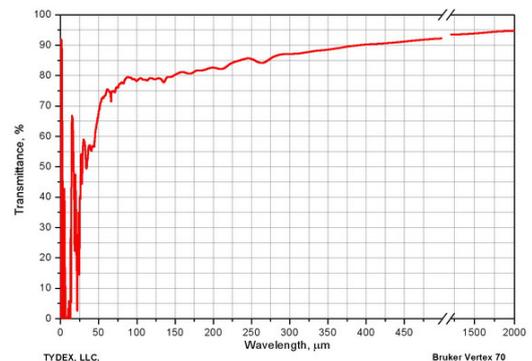


Fig. 7. Transmittance of TPX 2 mm-thick sample. THz region.

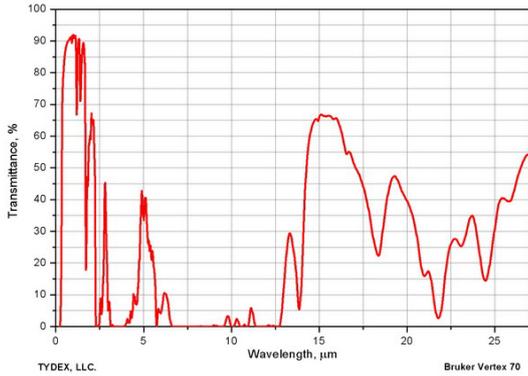


Fig. 8. Transmittance of a 2 mm thick TPX sample. NIR and MIR regions.

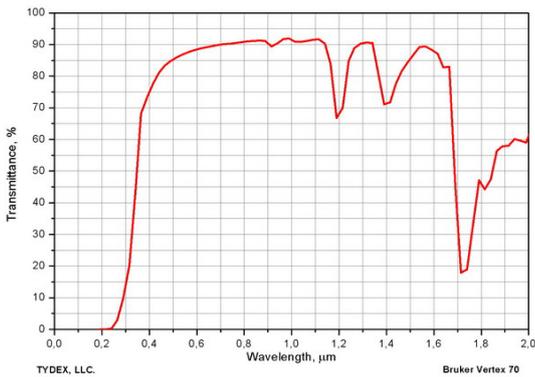


Fig. 9. Transmittance of a 2 mm thick TPX sample. UV, VIS & NIR ranges.

**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
Modulus of rupture	6100 psi

One more specific use of TPX should be mentioned. It can be used as an output window in CO<sub>2</sub>-pumped molecular gas lasers due to its transparency throughout the entire THz range, and absolute suppression of pumping radiation around 10 μm. TPX windows can also be used in cryostatic applications as “cold” windows. TPX transmittance in THz region is virtually temperature independent. Temperature coefficient of the refractive index is  $3.0 \cdot 10^{-4} \text{ K}^{-1}$  in the temperature range 8-120 K.

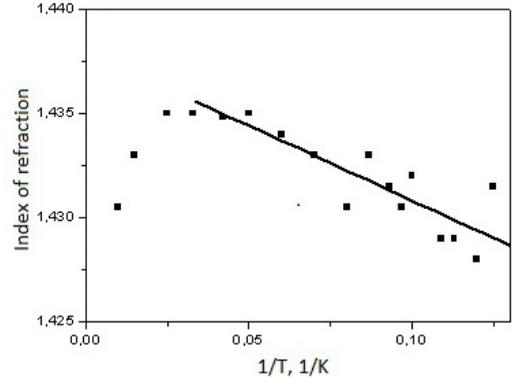


Fig. 10. Temperature dependence of refractive index. (\*\*)

Excellent optical properties of the TPX make it a good substitution for Picarin (Tsurupica) lenses.

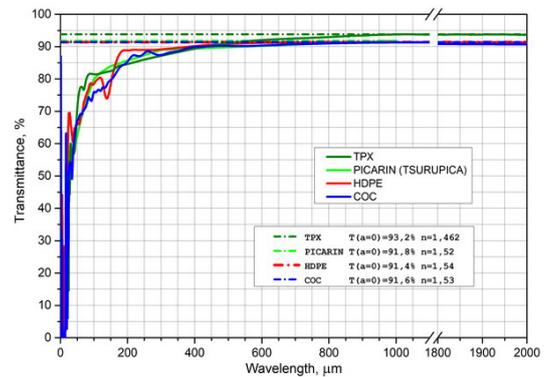


Fig. 11. Transmittance of 2 mm thick samples of TPX, PICARIN, HDPE and COC.

In vacuum applications TPX windows can be used down to  $10^{-9}$  mm Hg.

**2.2 Zeonex**

Besides that, we provide a cyclo olefin polymer ZEONEX® to use in an ultra-high vacuum environment ( $10^{-9}$  –  $10^{-11}$  mm Hg). It is characterized by excellent mechanical properties, good chemical stability and very low outgassing in a vacuum. Key characteristics of this material are given below.

*Typical ZEONEX properties:*

Density (ASTM D792)	1.01 g/cc
Tensile modulus (ISO527-2)	363000 psi
Elongation at failure (ISO527-2)	10 %
Bend strength (ISO178)	15100 psi
Bending modulus (ISO178)	363000 psi
Hardness (JIS K5401)	F
Heat deflection temperature (JIS D648)	122°C
Glass transition point (JIS K7121)	139°C
Thermal expansion coefficient (ASTM E831)	$6 \cdot 10^{-5} \text{ cm/cm}^\circ\text{C}$
Water absorption (ASTM D570)	<0.01%
Refractive index (ASTM D542)	1.531
Modulus of rupture	15100 psi

Similar to TPX, due to visible transparency and absence of refractive index dispersion, the ZEONEX terahertz optical systems can be adjusted using a HeNe laser beam. It should be noted that ZEONEX has better transmittance in visible region than TPX.

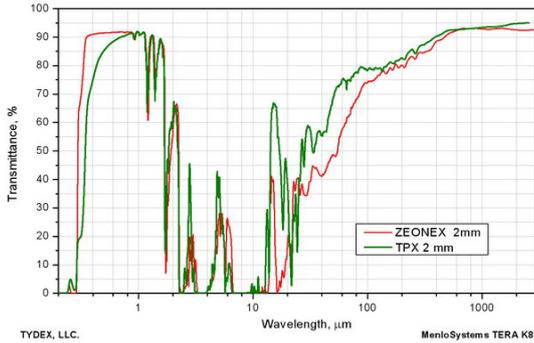


Fig. 12. Transmittance of 2 mm thick TPX and ZEONEX windows.

Better mechanical properties of ZEONEX as compared to TPX make it possible to manufacture prisms of this plastic.

### 2.3 Polyethylene (PE)

Polyethylene is widely used in different applications due its ready availability and low cost.

We use high density polyethylene (HDPE) for windows of Golay cells.

Typical HDPE properties:

Density	0.96 g/cm <sup>3</sup>
Tensile modulus (ISO 527)	1100 MPa
Shore D hardness (ISO 868)	64
Tensile yield point (ISO 527-1)	43 MPa
Tensile elongation (ISO 527-1)	9%
Linear thermal expansion coefficient (ISO 11359-1;2), 10 <sup>-5</sup> K <sup>-1</sup>	18
Operating temperature range (long-term)	-50 - +80 °C
Operating temperature range (short-term)	+90 °C

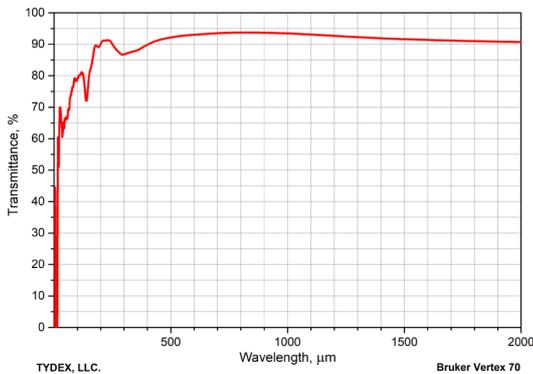


Fig. 13. Transmittance of a 2 mm thick HDPE sample. THz range.

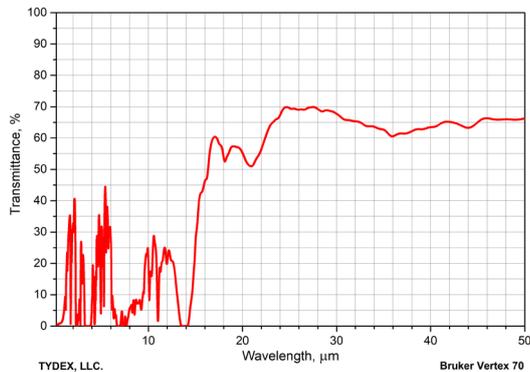


Fig. 14. Transmittance of a 2 mm thick HDPE sample. NIR and MIR regions.

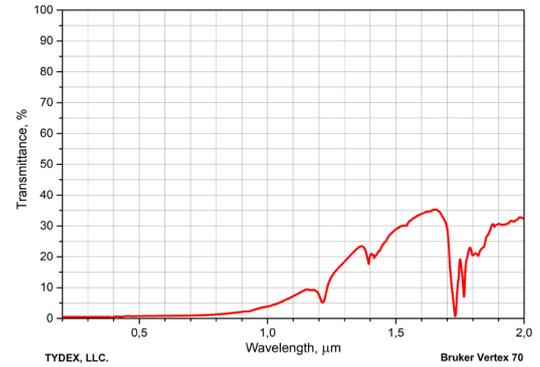


Fig. 15. Transmittance of a 2 mm thick HDPE sample. VIS & NIR ranges.

Unfortunately, HDPE has very low transmittance in visible range, thus it can't be used for adjustment of optical systems.

It should be noted that HDPE transmittance in the THz range is virtually temperature-independent, making it possible to use it both at liquid helium and liquid nitrogen temperatures. Temperature coefficient of the refractive index is  $6.2 \cdot 10^{-4} \text{ K}^{-1}$  in the temperature range 8-120 K.

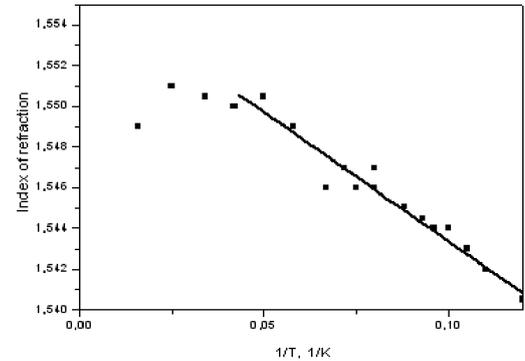


Fig. 16. Temperature dependency of the refractive index (\*\*\*).

In engineering applications, ultra-high molecular weight polyethylene is preferred because of its higher durability and lower friction coefficient as compared to HPDE.

Of all the grades of polyethylene, ultra-high molecular weight PE 1000 (UHMWPE) has the most balanced properties. This material combines excellent durability with great impact strength, even at low temperatures. It also has a good combination of rigidity and damping capacity and can be easily welded. It has low water absorption, resistant to most chemicals and can be machined easily.

UHMWPE is a great alternative for PTFE 4 at operating temperatures not exceeding 60-70°C.

Typical UHMWPE properties:

Density	0.93 g/cm <sup>3</sup>
Water absorption, % (ISO 62)	<0.01
Tensile modulus (ISO 527)	680 MPa
Shore D hardness (ISO 868)	63
Wear resistance (vs sand slurry)	80
Melting temperature	135 °C
Linear thermal expansion coefficient (DIN 53752), 10 <sup>-5</sup> K <sup>-1</sup>	150-230
Operating temperature range (long-term)	-250 - +80 °C



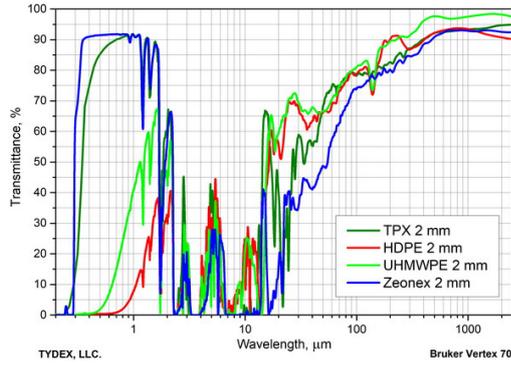


Fig. 21. Transmittance of 2 mm thick TPX, ZEONEX, HDPE and UHMWPE windows.

Crystalline materials such as silicon, quartz and sapphire demonstrate lower transmittance in THz region due to reflective losses. Specifically, it's 50-54% for silicon starting from 50  $\mu\text{m}$ , >70% for quartz from  $\sim 120 \mu\text{m}$ , >50% for sapphire from  $\sim 350 \mu\text{m}$  given 1-2 mm samples.

Please note we do not supply raw or semi-finished polymer and crystalline materials. We only deal in finished items. For the whole range of devices and components we supply for THz applications, please refer to the following sections of our site: THz assemblies, THz devices, THz polarizers, THz optics.

(\*) 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.