Optical properties of silicon, sapphire, silica and glass in the Terahertz range

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Abstract: Optical properties, refractive index and absorption coefficient, of silicon, sapphire, silica and pyrex glass near 1 THz frequency were determined by simple transmission measurements of THz pulses. Pulses were generated and detected in photoconductive antennas driven by 100 fs pulses coming from a mode-locked Ti:Sa laser. Refractive index of transparent materials were determined by measurement the delay of THz pulses and the absorption coefficients where derived of Fresnel losses.
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1. Introduction

The electromagnetic radiation whose frequency is limited by the microwave and infrared is called terahertz (THz). It is accepted that 100 GHz and 10 THz are the frequencies that limit the terahertz region. The low frequency limit is shared with the region of the millimeter-wave radio, where the emitters and detectors are devices based on microwave technology. On the other hand, the high frequency limit is the extreme infrared region where the optical devices operate. In both limits, the mechanisms of generation and detection of microwave or infrared fall greatly in their efficiency, so the THz spectral region was known as the *terahertz gap*.

In the past two decades new and higher power sources was used to demonstrate the potential of THz technology for physics research and commercial applications [1]. The mode-locked lasers that generate 100 fs pulses can be used to generate THz pulse beam sources. The THz pulses consist typically of a single cycle electromagnetic field in the frequency range of 0.2 THz to 3 THz that can be used to characterize a wide variety of materials [2]. This work is related with some materials that must be studied in order to build a THz spectrometer working in the time-domain, mainly glass, silica, sapphire and silicon.

2. Data Analysis Method

When synchronized or coherent optical pulses are used to generate-detect THz pulses, the temporal profile of the electric field of each THz pulse trace can be directly measured. In order to determine the optical properties of a material, THz pulses are recorded in the time domain with and without the sample, $E_s(t)$ and $E_r(t)$, placed near the detector antenna in the THz beam path of the set up of Fig. 1. From this time domain measurements, the time delay between the peaks of the signals t_d can be determined and the refractive index of the sample n can be calculated from,

$$n = 1 + \frac{c\,t_d}{d}\,, \tag{1}$$

where, c is the light velocity in air and d is the width of the sample.
From the peak values of the electric fields, $E_{s0}(t)$ and $E_{ro}(t)$, the intensity absorption coefficient α can be calculated if the Fresnel losses in both faces of the sample is considered,

$$\alpha = \frac{2}{d}\ln\frac{4nE_{r0}}{(1+n)^2 E_{s0}}\,. \tag{2}$$

When two samples of different widths are used, the Fresnel losses are cancelled, and the intensity absorption coefficient must be calculated as,

$$\alpha = \frac{2}{d_2 - d_1}\ln\frac{E_{20}}{E_{10}}\,. \tag{3}$$

Alternatively, both signal registered in the time domain, $E_s(t)$ and $E_r(t)$, can be Fourier-transformed into the complex amplitude, $E_s(\omega)$ and $E_r(\omega)$, and phases $\phi_s(\omega)$, $\phi_r(\omega)$, in the frequency domain, from which, the spectral refractive index and absorption coefficient, are,

$$n(\omega) = 1 + \frac{c}{\omega\, d}\, \Delta\phi(\omega), \tag{4}$$

$$\alpha(\omega) = \frac{2}{d} \ln \frac{4n(\omega)E_r(\omega)}{[1+n(\omega)]^2\, E_s(\omega)}, \tag{5}$$

where $\Delta\phi(\omega)$ is the intrinsic phase shift $\phi_s(\omega)$-$\phi_r(\omega)$.

3. Experimental Setup

The optoelectronic THz-TDS system used for our experiments is shown in Fig. 1. The key components for generating and detecting THz pulse radiation are photoconductive dipole antennas irradiated with 120 fs laser pulses coming from a mode-locked Ti:sapphire laser at 80 MHz. We used commercially avaible antennas [1], made on a low temperature-grown GaAs. The emitter antenna is biased with 30-40 V amplitude wave at the reference frequency (30 kHz). The emitted THz pulse is collimated using a highly resistive Si hyper-hemispherical lens with a diameter of 12.5 mm into a highly directional beam. The detector antenna has a similar Si lens that focuses the THz beam onto the electrodes where synchronized subpicosecond light pulses are producing electric carriers. Current driven by the THz electric field is measured by a lock-in amplifier at the reference frequency. Time delay in one of the arms, allows detecting the amplitude of the THz electric field in terms of time.

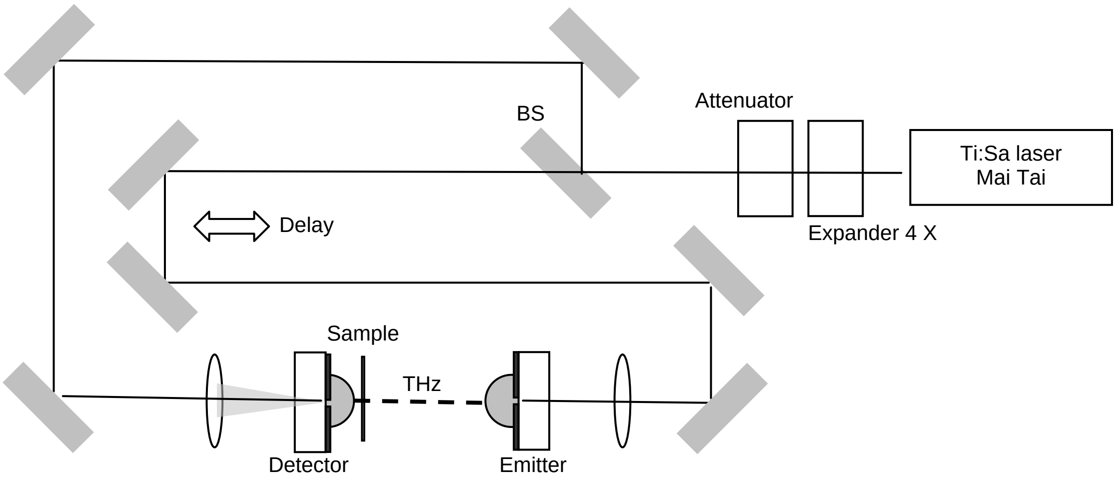

Fig. 1. Experimental set-up.

4. Results

Fig. 2 shows our results for the delay and the attenuation of THz pulses passing through two slabs of fussed silica (a) and two slabs of high-conductivity silicon and a commercial quality, random oriented, sapphire (b). Traces are vertically displaced. Measuring the time delay between different features of traces (maximum, minimum, zeroes) and the use of equations [1-3], the refractive index and the intensity absorption coefficients of these materials was calculated. Results are shown in Table I.

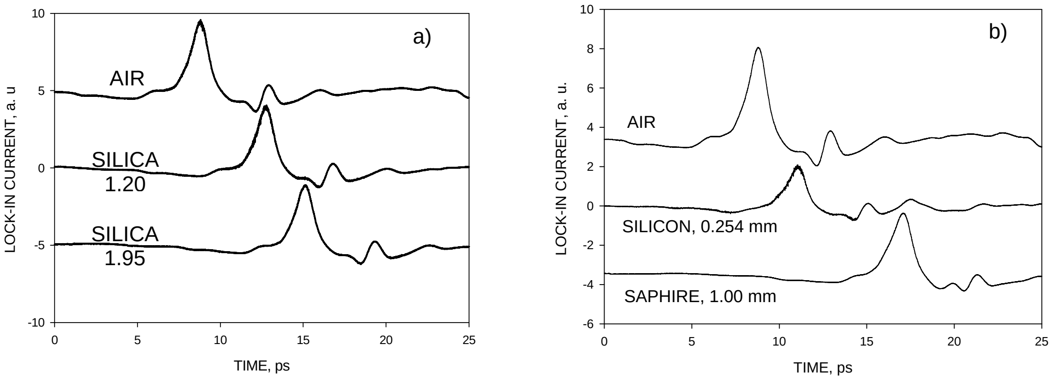

Fig. 2. Time delay of THz pulses in a) fused silica, and b) high-conductivity silicon and random commercial sapphire.

Table I. Refractive index and intensity absorption coefficients of studied materials.

Material	n	α (cm^{-1})	Comments
Silica	1.98 ± 0.02	4.2 ± 0.4	Eq. (3)
Silicon	3.56 ± 0.14	88 ± 7	High conductivity
Sapphire	3.31 ± 0.25	18 ± 4	Commercial quality

5. Discussion

Our results show that refractive indexes and intensity absorption coefficients, averaged over the bandwidth of the THz pulses, can be determined by measuring the time delay and the attenuation of the pulses produced by a slab of the material. Value obtained for silica can be compared with published results, $n = 1.95 \pm 0.05$; $\alpha = \pm$ cm^{-1}, obtained by spectral measurements in the same range of frequency [3, 4]. For silicon and sapphire, the values of α are correlated with the high conductivity and the poor quality of the sample[5, 6]. Spectral measurements were spoiled for water vapor that produces strong absorptions over 0.6 THz.

6. References

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