# Optical properties of human nails in THz frequency range

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**Abstract.** This work is devoted to investigation of optical properties (dispersion of refractive index, permittivity and absorption coefficient) of human nails in THz frequency range. These data were obtained by THz time-domain spectroscopy (TDS) technique in transmission mode. These results may be used to develop non-invasive technique of human pathologies control using nail as a reference sample in reflection mode of THz TDS. © 2016 Journal of Biomedical Photonics & Engineering.

**Keywords**: spectroscopy, nail, refractive index, permittivity, absorption, penetration depth

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## References

1. Classification and Diagnosis of Diabetes, Diabetes Care 38(Supplement_1), S8–S16 (2014).
2. A. Ceriello, and S. Colagiuri, "International Diabetes Federation guideline for management of postmeal glucose: a review of recommendations," Diabetic Medicine 25(10), 1151–1156 (2008).
3. L. Northam, and G. Baranoski, "A novel first principles approach for the estimation of the sieve factor of blood samples," Optics express 18(7), 7456–7469 (2010).
4. V. V. Tuchin, Tissue Optics: Light Scattering Methods and Instruments for Medical Diagnostics, SPIE-Intl Soc Optical Eng (2015). ISBN: 9780819495860
5. D. P. Popescu, and M. G. Sowa, "In Vitro Assessment of Optical Properties of Blood by Applying the Extended Huygens-Fresnel Principle to Time-Domain Optical Coherence Tomography Signal at 1300 nm," International Journal of Biomedical Imaging 2008, 1–6 (2008).
6. D. Yim, G. V. G. Baranoski, B. W. Kimmel, T. F. Chen, and E. Miranda, "A Cell-Based Light Interaction Model for Human Blood," Computer Graphics Forum 31(2pt4), 845–854 (2012).
7. A. Fitzgerald, E. Berry, N. Zinov'ev, S. Homer-Vanniasinkam, R. Miles, J. Chamberlain, and M. Smith, "Catalogue of human tissue optical properties at terahertz frequencies," Journal of Biological Physics 29(2-3), 123–128 (2003).
8. E. Pickwell, B. E. Cole, A. J. Fitzgerald, M. Pepper, and V. P. Wallace, "In vivo study of human skin using pulsed terahertz radiation," Physics in Medicine and Biology 49(9), 1595–1607 (2004).
9. P. H. Siegel, "Terahertz Technology in Biology and Medicine," IEEE Transactions on Microwave Theory and Techniques 52(10), 2438–2447 (2004).
10. J.-H. Son, Terahertz Biomedical Science and Technology, CRC Press (2014). ISBN 9781466570443
11. S. I. Gusev, M. A. Borovkova, M. A. Strepitov, and M. K. Khodzitsky, "Blood optical properties at various glucose level values in THz frequency range," Proc. SPIE 9537, 95372A (2015).
12. S. I. Gusev, N. S. Balbekin, E. A. Sedykh, Y. A. Kononova, E. V. Litvinenko, A. A. Goryachuk, V. A. Begaeva, A. Y. Babenko, E. N. Grineva, and M. K. Khodzitsky, "Influence of creatinine and triglycerides concentrations on blood optical properties of diabetics in THz frequency range," Journal of Physics: Conference Series 735, 012088 (2016).
13. A. Pashkin, M. Kempa, H. Němec, F. Kadlec, and P. Kužel, "Phase-sensitive time-domain terahertz reflection spectroscopy," Review of Scientific Instruments 74(11), 4711–4717 (2003).
14. M. M. Nazarov, A. P. Shkurinov, E. A. Kuleshov, and V. V. Tuchin, "Terahertz time-domain spectroscopy of biological tissues," Quantum Electronics 38(7), 647–654 (2008).

15. V. G. Bespalov, A. A. Gorodetskiĭ, I. Y. Denisyuk, S. A. Kozlov, V. N. Krylov, G. V. Lukomskiĭ, N. V. Petrov, and S. É. Putilin, "Methods of generating superbroadband terahertz pulses with femtosecond lasers," Journal of Optical Technology 75(10), 636–642 (2008).

## 1 Introduction

Diabetes mellitus is a group of metabolic diseases characterized by hyperglycemia resulting from defects in insulin secretion, insulin action, or both [1]. The chronic hyperglycemia of diabetes is associated with long-term damage, dysfunction, and failure of various organs, especially the eyes, kidneys, nerves, heart, and blood vessel. Accurate and efficient assessment of blood glucose concentration is critical in clinical management of many pathological conditions in human population. There is a direct relationship between the level of glucose in the blood of patients with diabetes and the probability of developing complications of the disease [2].

Optical properties of whole blood are important parameters in biophysical investigations and medical diagnostics. Variations in cellular and biochemical composition of whole blood markedly affect the values of different optical parameters (absorption, scattering, index of refraction etc.) [3-7].

One of the most important benefit of spectroscopy methods is the possibility of non-invasive analysis of media.8 Transmission mode of spectroscopy is common way for collecting data about easy extractable media [9, 10]. On the one hand transmission mode of medium analysis provides accurate results, but can be unsuitable for completely non-invasive investigation of biological tissues and fluids [11, 12]. On the other hand, reflection mode of spectroscopy cannot be used for direct blood optical measurement due to the location of blood below the surface of the human body [13]. Moreover, THz reflected signal considerably weakened due to the water contained in the skin layer. Despite this, capillar blood located in fingers' nail beds may be investigated through the nails in the reflection mode (see Fig. 1).

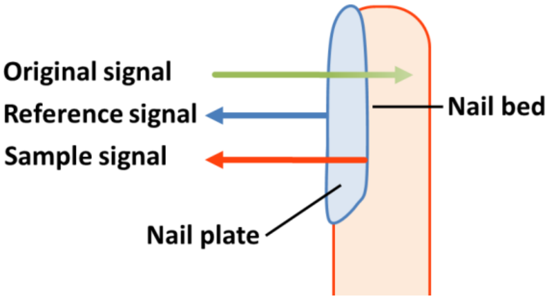


Fig. 1 Scheme of non-invasive reflective spectroscopy of the capillar blood inside the nail bed.

At this variant of reflective spectroscopy, it is need to know optical properties of nail plate for analysis of nail bed spectral data. It is not enough papers with detailed data about optical properties of human nails in THz frequency range. For example, in the Ref. [14] it was shown only refractive index and dispersion of absorption coefficient of nails. This work is dedicated to retrieve optical properties of human nails for purposes of non-invasive glucose measuring technology.

## 2 Experimental setup

The optical properties of nail plates were studied in the frequency range of 0.1-1 THz using time-domain spectrometer in transmission mode [11, 15]. The scheme of the setup is shown in the Fig. 2.

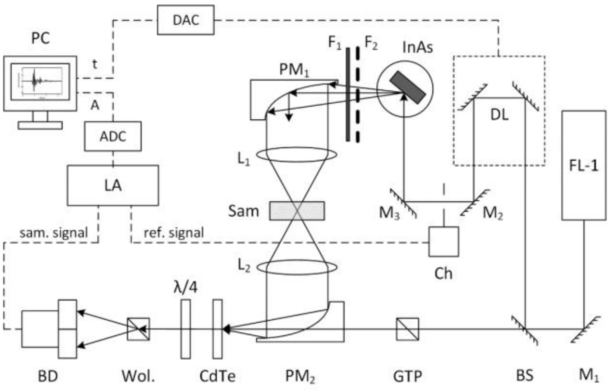


Fig. 2 Schematic diagram of the set up (FL-1 – femtosecond laser based on potassium-yttrium tungstate crystal activated with ytterbium (Yb: KYW), generating femtosecond pulses; F1, 2 – a set of teflon filters for IR wavelength range cutting off, BS – beamsplitter, DL – optical delay line, $M_{1,\ 2,\ 3}$ – mirrors, Sam – investigated sample, Wol. – Wollaston prism, CdTe – electro optical cadmium-telluric crystal, BD – balanced detector, LA – lock-in amplifier, PC – personal computer, GTP – Glan-Taylor prism, $PM_{1,\ 2}$ – parabolic mirrors, Ch – chopper, DAC – digital to analog converter, ADC – analog to digital converter

Broadband pulsed THz radiation is generated using a InAs semiconductor in the magnetic field of 2 T by irradiating it with femtosecond pulses of an Yb: KYW laser (wavelength of 1040 nm, the pulse duration of 120 fs, the pulse repetition frequency of 75MHz, the power of 1 W). THz radiation has the following output characteristics: the spectral range from 0.05 to 2 THz, the average power up to 30 μW, the pulse duration of 2.7 ps. The main power is concentrated at the frequency range from 0.12 to 1.1 THz. THz radiation passes through a teflon filter (which cuts the wavelengths shorter than 50 μm). After that, the radiation passes through the sample fixed in a focal plane perpendicularly to the beam. THz sample pulse affects on the anisotropy of the electrooptical CdTe crystal. As a result, THz pulse induces birefringence of the probe beam in the crystal due to the electrooptical effect. The birefringence magnitude is directly proportional to the intensity of terahertz wave electric field in the time point E(t). These data are required to calculating E(ω) using Fourier transform.

## 3 Sample preparation

There are 10 different nails measured at this experiment. The nail samples were taken from hands of man corpse (Fig. 3).

Fig. 3 Investigated nail samples.

Thicknesses of each nail were measured 10 times with micrometer. This feature helps to decrease error caused by thickness measuring (the most significant error in transmissive TDS of thin structures). Determination of samples thicknesses is shown in Table 1.

Each sample of nail plate was prepared for recording of transmission time-amplitude signal: there were the same zones of nail plates for thickness measuring and signal transmission (Fig. 4). The diameter of the THz pulse spot is 3 mm. Dried nail plates had not any other specific treatment before experiment.

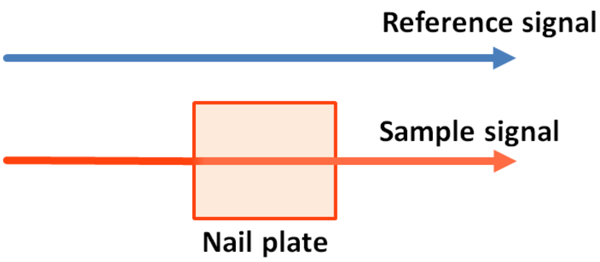


Fig. 4 Scheme of recording time-amplitude signal.

Table 1 Measured thickness values of nails, used in experiment.

| Exp. № | Thickness of sample №x, μm | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 450 | 420 | 450 | 410 | 420 | 460 | 410 | 430 | 430 | 360 |
| 2 | 460 | 410 | 420 | 440 | 410 | 490 | 370 | 450 | 460 | 390 |
| 3 | 520 | 460 | 410 | 390 | 450 | 470 | 480 | 410 | 470 | 390 |
| 4 | 430 | 450 | 430 | 410 | 380 | 490 | 460 | 420 | 460 | 410 |
| 5 | 490 | 440 | 410 | 400 | 390 | 490 | 460 | 430 | 440 | 430 |
| 6 | 510 | 450 | 480 | 450 | 420 | 490 | 400 | 390 | 430 | 380 |
| 7 | 490 | 420 | 420 | 420 | 440 | 470 | 400 | 390 | 450 | 430 |
| 8 | 460 | 460 | 430 | 400 | 450 | 470 | 410 | 430 | 460 | 330 |
| 9 | 480 | 450 | 420 | 400 | 410 | 490 | 400 | 400 | 450 | 440 |
| 10 | 540 | 450 | 420 | 410 | 420 | 480 | 390 | 420 | 440 | 430 |
| Average | 483±27 | 441±15 | 429±15 | 413±14 | 419±17 | 480±10 | 418±29 | 417±16 | 449±11 | 399±29 |

## 4 Data acquisition

For each sample, a time-amplitude transmission waveform was taken 100 times and averaged for each timepoint. Also it was taken reference transmission waveform of air. All the acquired reference and sample waveforms were converted by Fourier transformation into $E_{ref}(\omega)$ and $E_{sam}(\omega)$, respectively. Then the THz electric field is:

$$\hat{E}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} f(t)\, e^{-i\omega t} dt = E_0(\omega) e^{-i\varphi(\omega)} \quad (1)$$

where f(t) is the time-amplitude waveform, ω is the angular frequency, $E_0(\omega)$ is the amplitude data, φ(ω) is phase data.

The real part of refractive index $n_{real}$ calculated as:

$$n_{real}(f) = 1 + \frac{c\left(\varphi_{sam}(f) - \varphi_{ref}(f)\right)}{2\pi l f} \quad (2)$$

where c is the speed of light in vacuum, l is the thickness of medium, f is the frequency.

The absorption coefficient $\alpha$ is calculated using the amplitude data:

$$\alpha(f) = \frac{1}{l} ln \left( \frac{E_{0\,ref}(f)}{E_{0\,sam}(f)} \right)^2 \qquad (3)$$

The penetration depth $L$ is reverse function to the absorption coefficient $\propto$.

The imaginary part of the refractive index $n_{imag}(f)$ requires data about the absorption coefficient $\propto$:

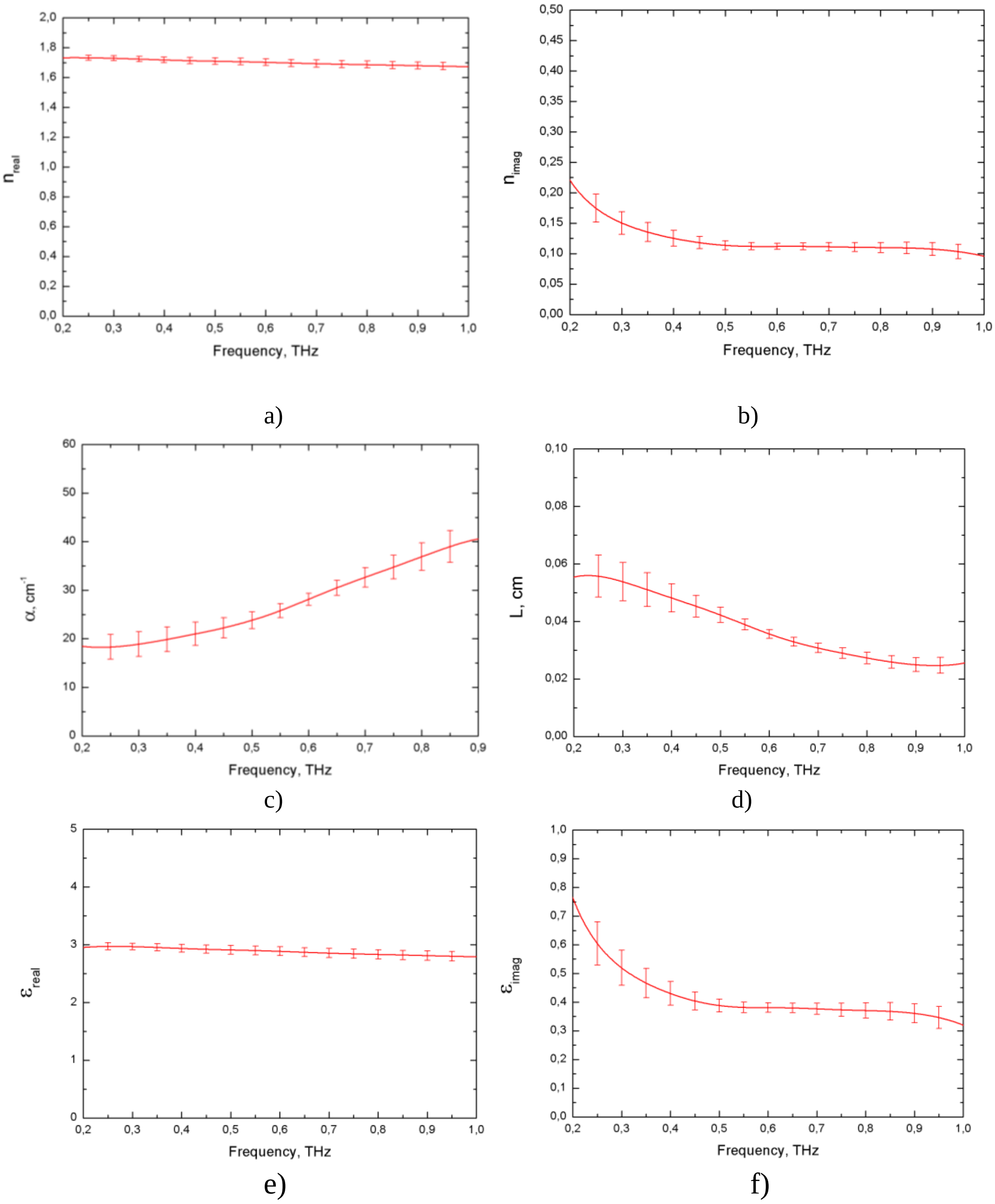
$$n_{imag}(f) = \frac{\mu(f)\, c}{4\pi f} \qquad (4)$$

Both parts of the complex permittivity ε use both parts of the refractive index n:

$$\varepsilon_{real}(f) = n_{real}^2(f) - n_{imag}^2(f) \qquad (5)$$

$$\varepsilon_{imag}(f) = 2\, n_{real}(f)\, n_{imag}(f) \qquad (6)$$

All of these optical properties available as results of Spectrina software [11].



a) b)

c) d)

e) f)

Fig. 5 Frequency dispersions of optical propreties of: a) real part of refractive index $n_{real}(f)$, b) imaginary part of refractive index $n_{imag}(f)$, c) absorption coefficient μ(f), d) penetration depth $L(f)$, e) real part of permittivity $\varepsilon_{real}(f)$, f) imaginary part of permittivity $\varepsilon_{imag}(f)$.

## 5 Results and Discussions

Based on 10 samples, we investigated the frequency dispersions of $\mathrm{n_{real}}$, $\mathrm{n_{imag}}$, $\propto$, $\mathrm{L}$, $\varepsilon_{\mathrm{real}}$, $\varepsilon_{\mathrm{imag}}$ in the frequency range of 0.2 to 1.0 THz (see Fig. 5).

Enough amount of samples and measurements provides the result with a low level of error. The real part of refractive index has stable value of 1.70 ± 0.03 in the frequency range of 0.2 – 1.0 THz. The imaginary part of refractive index has inverse ratio on frequency in the frequency ranges of 0.2 – 0.5 THz (from 0.22 ± 0.03 to 0.11 ± 0.01) and of 0.9 – 1.0 THz (from 0.11 ± 0.01 to 0.10 ± 0.01), but has fixed value of 0.11 ± 0.01 at the frequency range of 0.5 – 0.9 THz. The absorption coefficient has direct ratio on frequency in the frequency range of 0.2 – 0.9 THz (from 18 ± 3 $\mathrm{cm^{-1}}$ to 40 ± 4 $\mathrm{cm^{-1}}$). The penetration depth has inverse correlation with frequency in the frequency range of 0.2 – 0.9 THz (from 0.055 ± 0.008 cm to 0.025 ± 0.002 cm). The real part of permittivity has stable value of 2.89 ± 0.08 in the frequency range of 0.2 – 1.0 THz. The imaginary part of permittivity has inverse ratio on frequency in the frequency ranges of 0.2 – 0.5 THz (from 0.76 ± 0.10 to 0.39 ± 0.02) and 0.9 – 1.0 THz (0.36 ± 0.03 to 0.32 ± 0.04) and fixed value of 0.38 ± 0.02 in the frequency range of 0.5 – 0.9 THz.

These results are dispersions, but not constants. At the same time, some frequency ranges with stable value are suitable for using nail as reference medium. Moreover, all 10 measured nail plates have same optical properties within the margin of error. The absorption coefficient of nail plates increases with the frequency increasing. Therefore, using of low frequency of THz range is more efficient for measuring glucose levels.

In the Ref. [14] it was shown only the refractive index and the dispersion of the absorption coefficient obtained using reflection THz TDS in the frequency range of 0.25 – 2.0 THz. It this paper we obtained all optical properties as dispersions such as the complex refractive index $\mathrm{n(f)}$, the absorption coefficient $\alpha(\mathrm{f})$, the penetration depth $\mathrm{L(f)}$, the complex permittivity $\varepsilon(\mathrm{f})$.

## 6 Conclusion

The dispersions of nail plates optical properties (the complex refractive index $\mathrm{n(f)}$, the absorption coefficient $\alpha(\mathrm{f})$, the penetration depth $\mathrm{L(f)}$, the complex permittivity $\varepsilon(\mathrm{f})$) were obtained in the frequency range of 0.2 – 1 THz by THz TDS. These data will be helpful for development of the reflective non-invasive spectroscopic method of blood glucose measuring technique. Due to the radiation penetration depth is more than the nail plate thickness in the frequency range of 0.2 – 0.5 THz, that the radiation of this range can be used for nail bed investigation. Nail could be used as reference layer for investigation of capillar blood by reflection THz TDS.

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