Dielectric Anisotropy of Human Bone in Spectral Range 0.2 to 2.5 THz

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Terahertz time domain spectroscopy (THz-TDS) was applied to study anisotropic properties of a human jawbone in transmission geometry. The fiber femtosecond laser (Fx-100, IMRA) with a pulse width of 113 fs, a central wavelength of 800 nm and an average power of 120 mW was used as a laser source for pumping and detecting terahertz pulses. The polarization of the THz pulse is linear. The experimental results indicate that the refractive indices n(ω) and the absorption coefficients α(ω) of a human jawbone change with the alteration of the direction of the linear polarization vector of the electric field of THz pulse relative to the axis of the plate of the human jawbone.

I. Introduction

A bone material is composed of an organic matrix of collagen fibers and mineral hydroxyapatite ($Ca_5(PO_4)_3OH$), nanoparticles. An average tooth dentin contains 70% hydroxyapatite crystals, 20% collagen (e.g., proteins), and 10% water. The organic constituents provide flexibility, whereas the mineral provides strength. Due to the specific arrangement of mineral platelets and collagen fibrils with respect to the main axis in case of a long bone, signals relative to vibrational units of both mineral and collagen can result highly anisotropic. Up to now, very few studies have been conducted concerning the study of the human bones [1, 2] and its anisotropy by THz radiation [3].

Many biological tissues are structurally anisotropic. Tissue birefringence results from the linear anisotropy of fibrous structures, which forms the extracellular media. The refractive index of a medium is higher along the length of fibres than along their cross section [3]. A tissue structure is a system composed of parallel cylinders that create a uniaxial birefringent medium with the optic c- axis parallel to the fibrils (ciliders) axes (Fig.1a). A structure of parallel dielectric cylinders immersed in isotropic homogeneous ground substance behaves as a positive uniaxial birefringent medium. The hidroxyapatite can be found in space between cylinders - collagen fibrils periodically separated by a tiny gap from 1 nm to 40 nm (Fig.1b).

In this paper we report the results obtained from a study of dielectric anisotropic properties of a human jawbone in transmission geometry using THz time-domain spectroscopy (THz -TDS).

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$\Delta n_{oe} = (n_e - n_o) > 0$

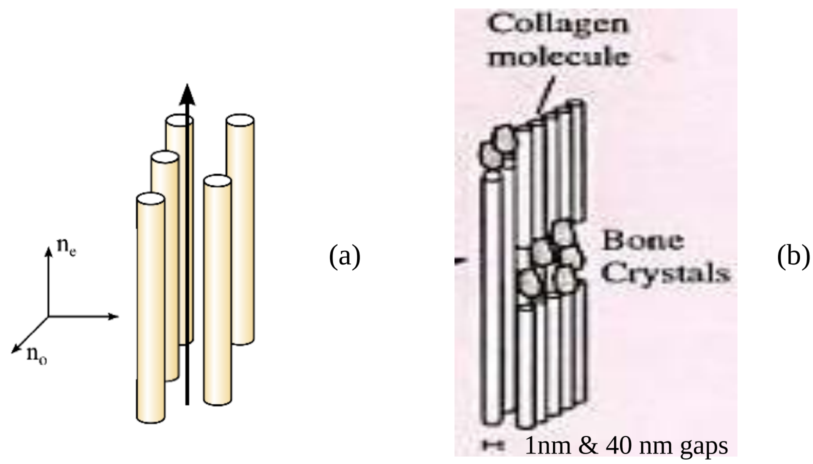

Fig.1. System of long dielectric cylinders with diameters ranging from 20 to 400 nm (a). The hidroxyapatite can be found in space between cylinders - collagen fibrils periodically separated by a tiny gap from 1 nm to 40 nm (b).

II. EXPERIMENTAL TECHNIQUE

A schematic arrangement of the THz-TDS system, demonstrating the principal configuration used to obtain THz spectral data, is shown in Fig.2. The fiber femtosecond laser (Fx-100, IMRA) with a pulse duration of 112 fs, a central wavelength of 800 nm and an average power of 120 mW was used as a laser source for pumping and detecting terahertz pulses. The laser output, in the form of high repetition frequency - 75 MHz, is divided into two optical paths - the pump and probe beams. The pump beam is focused into a gap between biased electrodes deposited upon the surface of gallium arsenide. The pumping pulses have photon energy (1.43 eV) above the direct band-gap of the GaAs thas inducing conductivity changes. Electron–hole pairs are created by each laser pulse in a semiconductor, which, when accelerated by the bias field, act as a transient current source. The transient current radiates a sub-picosecond, single-cycle coherent THz electric pulse, Fig.3a. The THz pulse from photoconductive antenna (PCA) is emitted in a dipole like pattern. The resulting radiation is polarized along the direction of the bias field. The polarization ratio is usually better than 10:1.

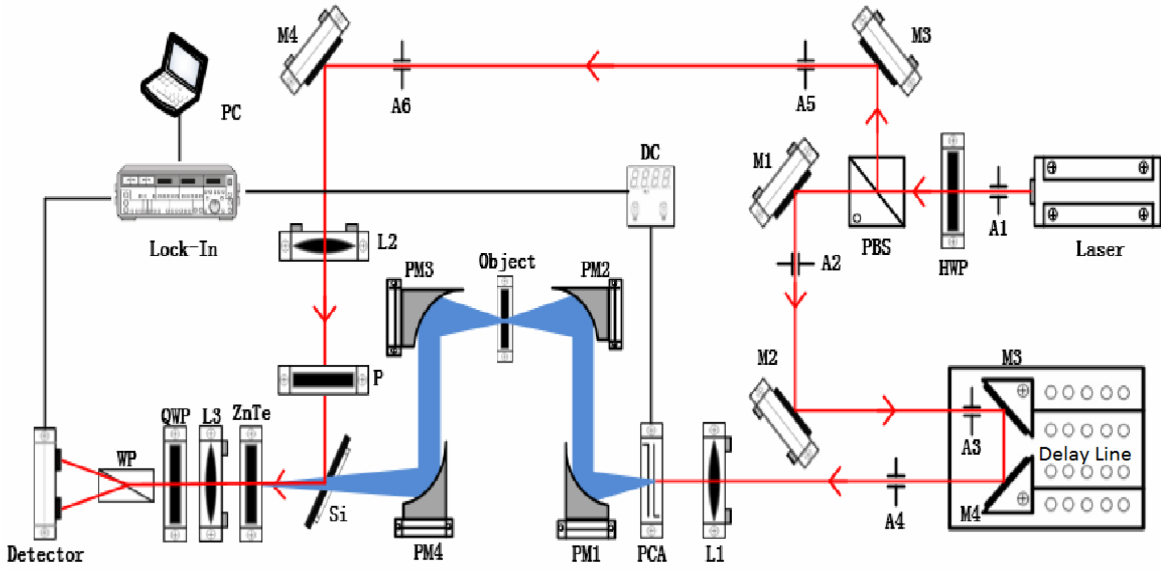

Fig.2. Schematic diagram demonstrating the principles of a THz-TDS experiment

The THz pulse after PCA is collected and directed to the object using parabolic mirrors (PM). The THz radiation transmitted through the object is then directed by two PM towards a detector. A small fraction of the pump optical beam - probe beam, was used for coherent detection of transmitted radiation from the object (jawbone) using a dynamic free-space electro-optic cell. This consists of electro-optic crystal – ZnTe with a (110) crystal orientation, a quarter-wave plate providing optical bias, and the Wollaston prism (WP) as the analyzer. Thus, the whole system represents a version of a coherent pump-probe spectroscopic setup [4].

The electro-optic sampling method is widely applied for the coherent detection of THz pulse due to its short response time, high sensitivity and wide bandwidth. For the EO sampling, the phase-matching condition (Fig.3a,b) requires the group velocity of probe pulse equal to the phase velocity of THz pulse. The phase mismatch is defined as [5]

$$\Delta k = \frac{f_{THz}}{c}(n_{THz}(f_{Thz}) - n_g(f_{probe}))$$

The amplitude of detection response is proportional to the thickness of crystal ZnTe at the phase-matching condition, but a thicker crystal results in the reduction of bandwidth of THz pulse. The compromise should be made between the detection response and bandwidth. We used a ZnTe crystal of 1 mm thickness, ipso facto to provide the coherent detection of THz pulse in spectral range from 0.2 THz to 2.7 THz.

Using interferometric control over the optical delay between the pump and probe pulses, the time domain dependence of THz electric field is recorded. The balanced electro-optic detection method provides an excellent signal to noise ratio >1500 (to a noise-limited frequency of 3 THz) by the use of phase sensitive amplification with a lock-in amplifier. Two spectra, THz field and phase, are processed via a fast Fourier transform from originally obtained time-domain dependence. Although the spectrum of bone [2] in THz region was reported, the response of the jawbone tissue to polarized light is still unknown.

THz time-domain transmission spectroscopic properties of the jawbone is presented in Fig. 3 and Fig. 4.

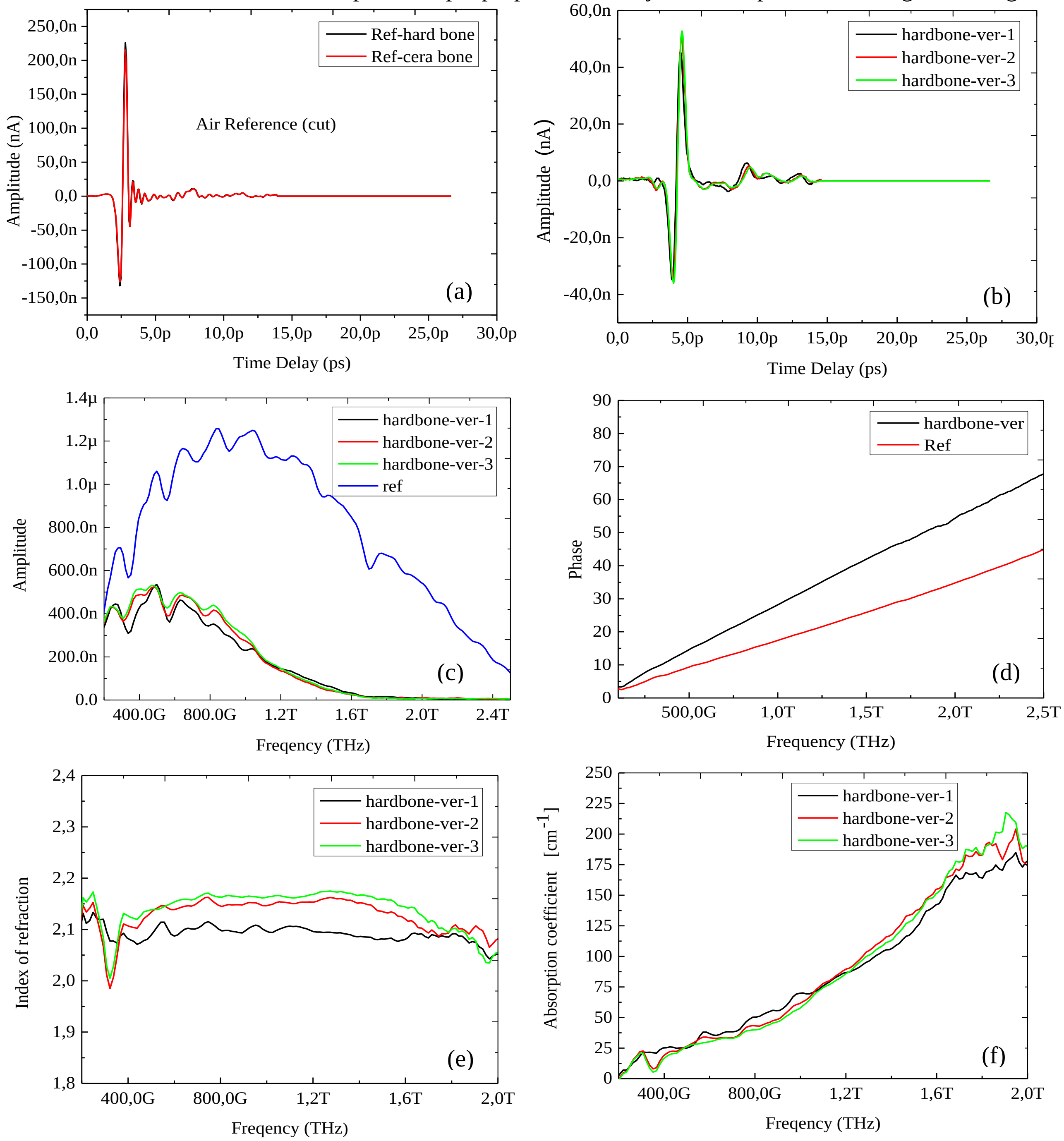

Fig.3. Temporal waveforms of THz pulses transmitted through (a) the air and (b) jawbone, THz amplitude spectra of the fields after a FFT (c); phase-frequency response (d); refractive index (e) and absorption coefficient human jawbone (f). The THz pulse polarization is parallel to the bone axis.

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Temporary forms of the reference pulse $E_1(t)$ (Fig. 3a), transmitted through free space - the air, and then the pulse $E_2(t)$ passed through the jawbone of thicknesses d = 0.44 mm (Fig. 3b) were measured. To demonstrate the reproducibility of the experiment on Fig. 3 (b, c, e, f) the curves of three consecutive measurements are given.

The index of refraction **n(ω)** and absorption coefficient **α(ω)** for different directions of the laser polarization are depicted in Fig.4c and Fig.4d.

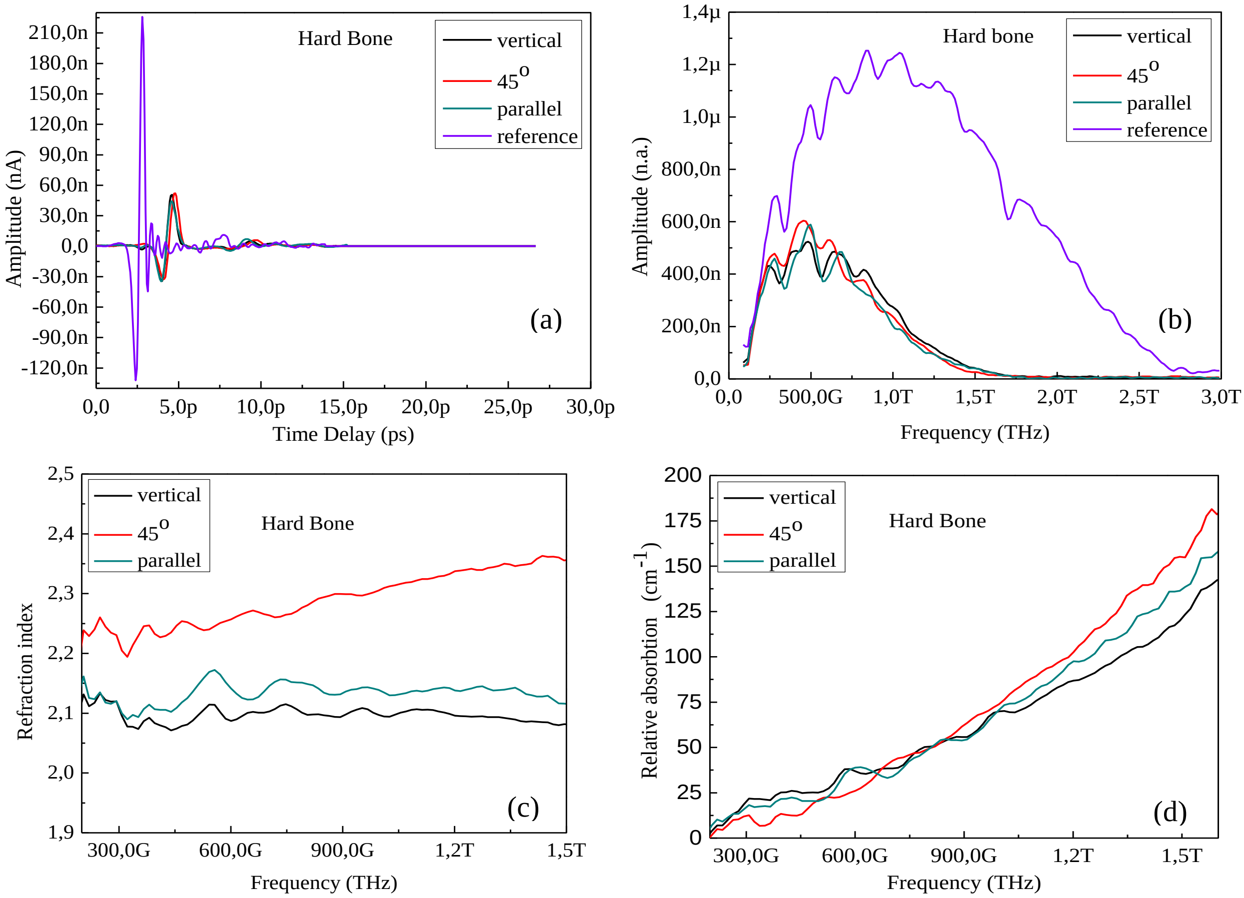

Fig.4. The index of refraction n(ω) and absorption coefficient α(ω) for different directions of the laser polarization (vertical, 45°, and parallel to the bone axis), in the spectral range of 0.2-2.5 THz.

III. CONCLUSIONS

Dielectric anisotropy of a human jawbone has been studied using THz time-domain transmission spectroscopy in the wide frequency range 0.2–2.5 THz. The refractive index n(ω) and absorption coefficient α(ω) for different directions of the THz pulse polarization were measured. The difference n(ω) and α(ω) in different directions at any frequency can be associated with the structural anisotropy of a bone that is, both with different dimensions of the bone particles and a specific tissue structure. This is the first representation of the frequency-dependent refractive index n(ω) and absorption coefficient α(ω) of jawbone.

IV. REFERENCES

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