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

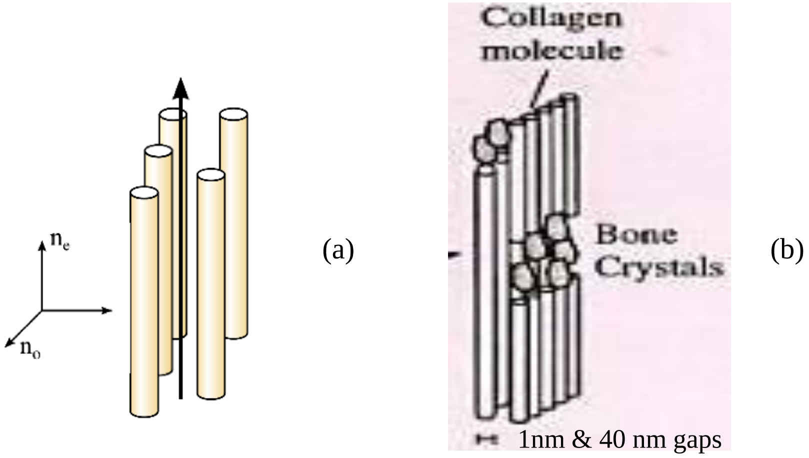

Fig.1. System of long dielectric cylinders with diameters ranging from 20 to 400 nm (a). The hidroxyapatite can be found in space between cylinders - collagen fibrils periodically separated by a tiny gap from 1 nm to 40 nm (b).

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.

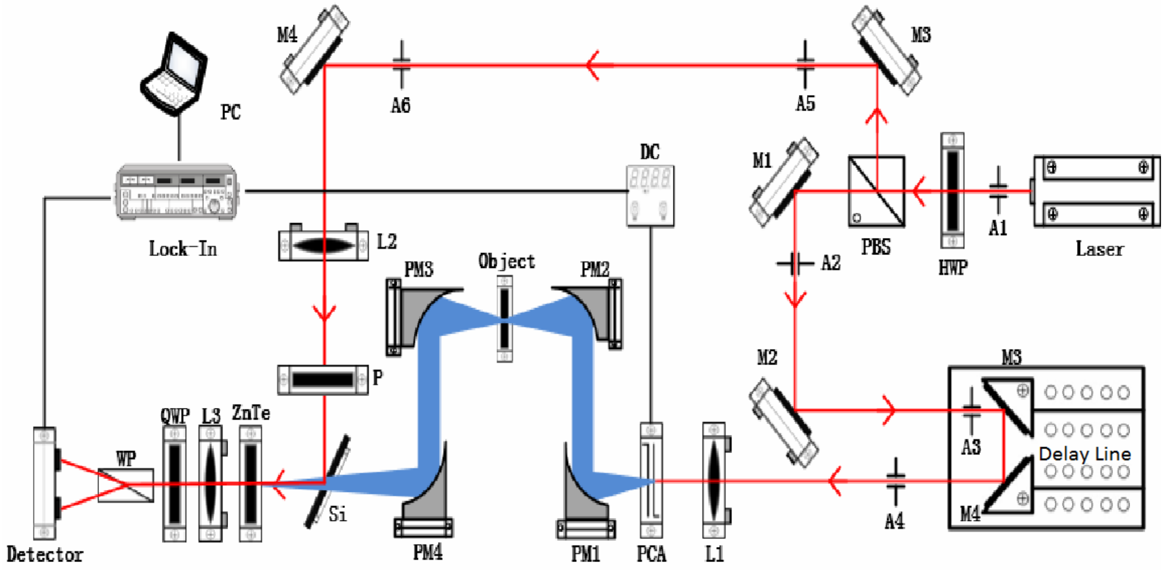

Fig.2. Schematic diagram demonstrating the principles of a THz-TDS experiment

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.

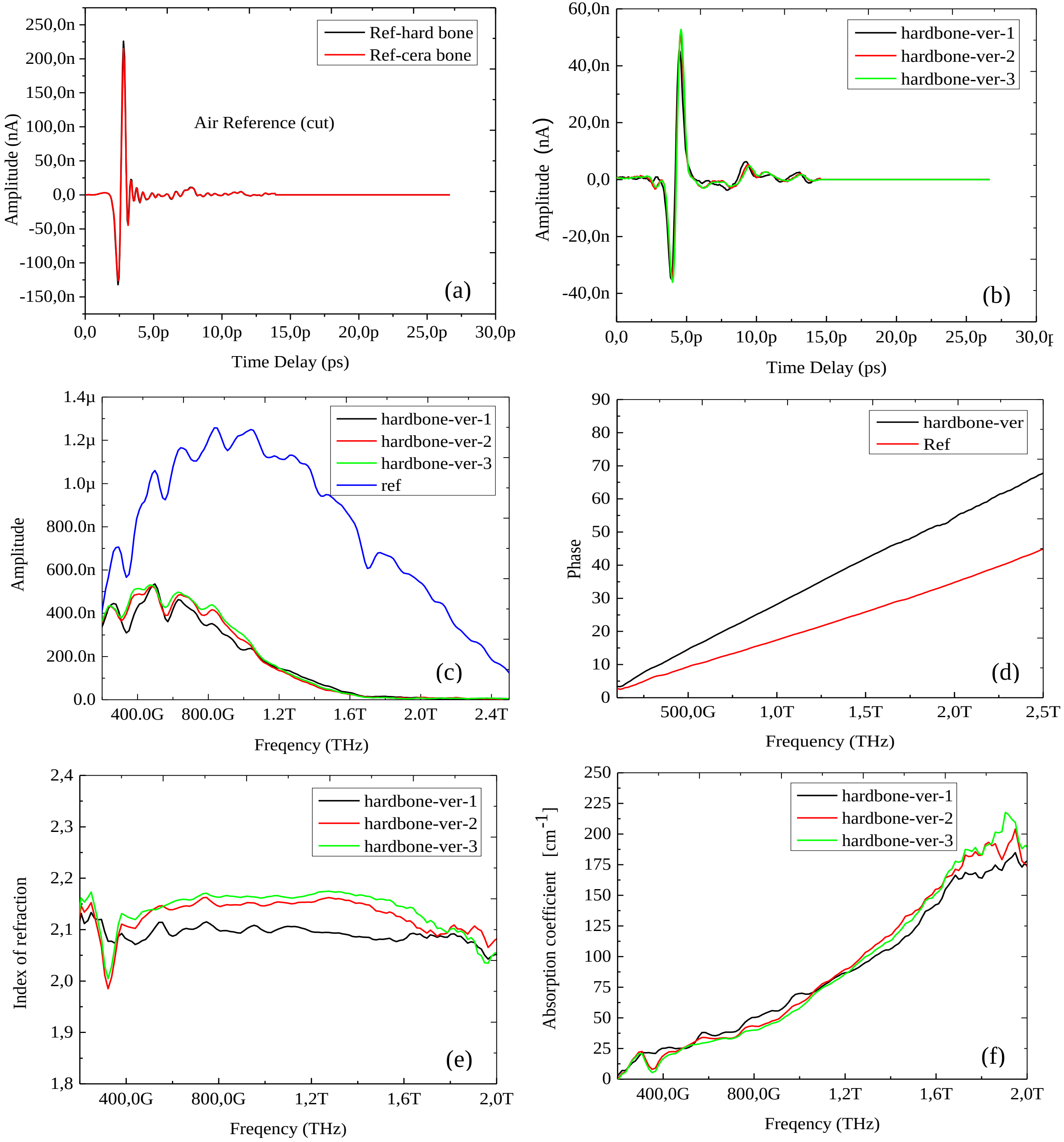

Fig.3. Temporal waveforms of THz pulses transmitted through (a) the air and (b) jawbone, THz amplitude spectra of the fields after a FFT (c); phase-frequency response (d); refractive index (e) and absorption coefficient human jawbone (f). The THz pulse polarization is parallel to the bone axis.

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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.

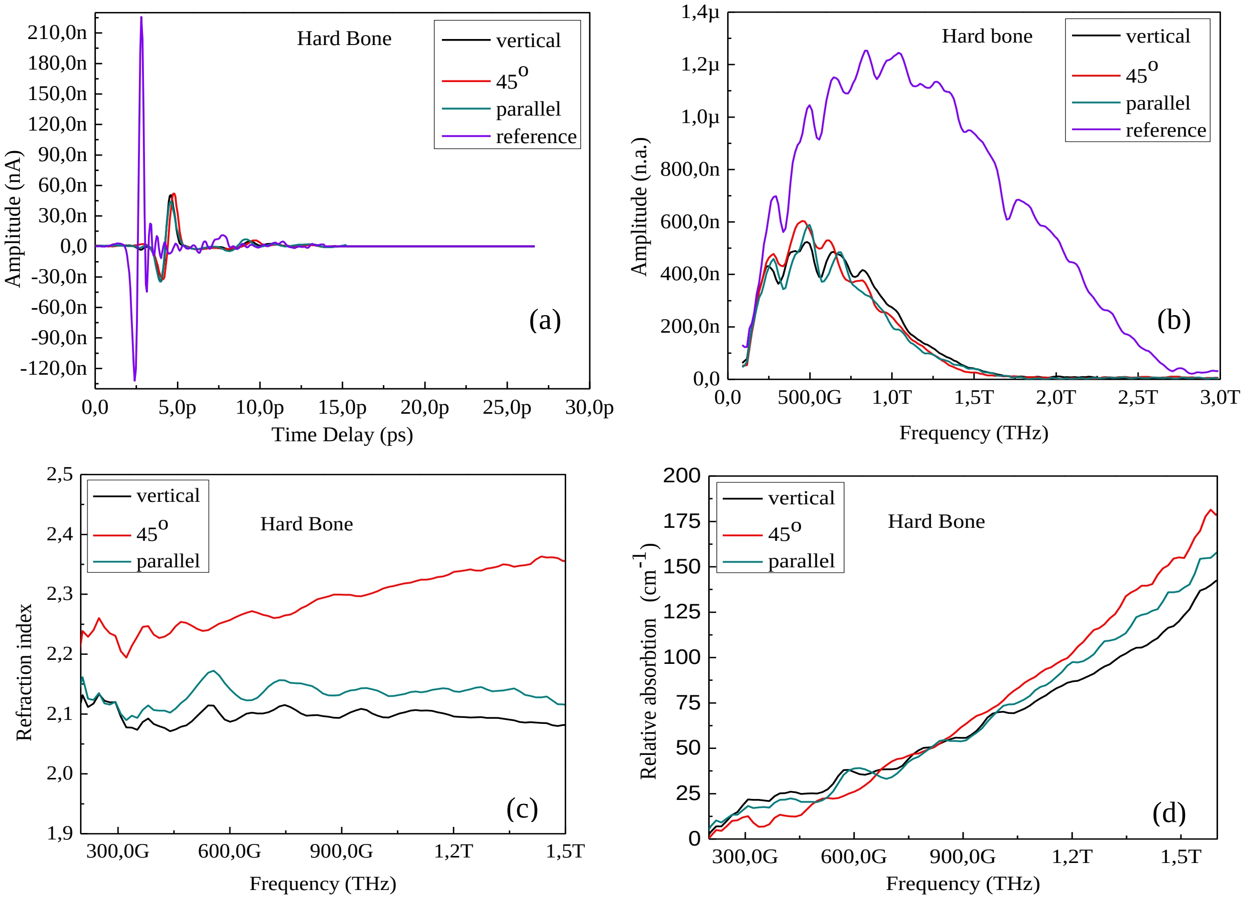

Fig.4. The index of refraction n(ω) and absorption coefficient α(ω) for different directions of the laser polarization (vertical, 45°, and parallel to the bone axis), in the spectral range of 0.2-2.5 THz.

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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Terahertz Pulses Generation via Optical Rectification in LiNbO3 Crystal by Step-Wise Phase Mask

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Generation of the broadband terahertz (THz) radiation via optical rectification of femtosecond laser pulses in the single-domain lithium niobate crystal equipped with the step-wise mask (SWM) was investigated. It was shown that by using SWM is possible to achieve phase matching for the spectral components of the terahertz pulse in the wide frequency range, thus ensuring efficient conversion of laser radiation in the terahertz range.

The efficiency of the THz radiation, depending on the parameters of SWM was investigated. The radiation pattern of THz generation and the temporal characteristics of THz pulses for different numbers of the step of SWM were analyzed. It was shown that with increasing number of SWM steps, the magnitude of THz field strongly grows and shrinking at the same time the radiation pattern.

I. INTRODUCTION

The electromagnetic waves of terahertz range (~ 0.l ÷ l0 THz) occupy an intermediate region between the microwave and infrared frequency ranges and are of considerable interest for various applications in the fields of the high-speed communications, molecular spectroscopy, medical diagnostics, in the security systems, for visualization of objects, and etc. [l, 2]. Despite the big breakthrough of the last decades in the field of terahertz radiation sources, this area remains one of the technically poorly secured part of spectrum. This encourages many researchers to seek new methods to create the highly effective and affordable terahertz sources with the necessary parameters for the variety of applications. For many applications there is a need for the broadband THz pulses. In particular, the ultrabroadband terahertz video pulses are ideal for the time-domain spectroscopy technique [3, 4].

The difference frequency generation and the optical rectification of femtosecond laser pulses are the widely used methods for generating the terahertz radiation [4, 5]. It was shown in [6–8] that using the wide-aperture beams in the transverse direction of periodically polarized lithium niobate crystal one may obtain the quasi-monochromatic generation of terahertz radiation with the center frequency determined by the spatial period Λ of periodically polarized lithium niobate crystal (PPLN). The periodically inverted domain structure of the PPLN crystal is used to produce the constructive interference of terahertz waves radiated from the separate regions of the PPLN. However, the oscillation frequency in this case is predetermined by the spatial period of the PPLN domain structure and therefore it cannot be changed after the sample preparation.

To overcome this disadvantage in the generation of narrow-band terahertz radiation, the single-domain lithium niobate crystal with the variety of the phase masks (PM) recently has been used. With the shadow or binary PM located in front of the single-domain nonlinear $LiNbO_3$ crystal, the virtual quasi-periodic structure is formed that provides the phase matching for the specific frequency of terahertz radiation. The frequency of the radiation can be tuned by change of the spatial period Λ of PM.

However shadow or binary PM cannot be used for generation broadband THz pulses. To overcome this problem in [8] was presented a new method for efficient THz-pulses generation by OR in the single-domain lithium niobate crystal. It's based on using the step-wise mask (SWM) (Fig. 1), which provide quasi-linear time delay of femtosecond laser pulses along cross-section of the optical beam, thus forming a tilted amplitude front of beam.

II. BROADBAND PHASE MATCHING BY USING SWM

In the case of SWM, in contrast to the diffraction grating, the formed laser beam until the nonlinear crystal extend not in the air, but in mask, wherein wavelength of the radiation is less than in the air. This reduces the beam distortion associated with diffraction scattering.