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Nonlinear Properties of Biological Nerve Fiber System in THz Spectrum Range

(Submitted by Academician R. M. Martirosyan 08/X 2024)

Keywords: *THz, nerve fiber, neural network, nonlinear properties, nonlinear transformation.*

Introduction. In the central nervous system of living organisms, information is transmitted through nerve fibers by electrical impulses [2]. According to various studies [1, 5–7], based on the geometric dimensions and electrical properties of nerve fibers, it is hypothesized that information exchange through nerve fibers may occur via electromagnetic waves in the terahertz or infrared range. Despite these hypotheses and corresponding theoretical models, no experimental studies are known to us that confirm or refute the exchange of information through nerve fibers via waves in these ranges. Recently, in our works [3, 4], the behavior of the animal's nerve fiber system in the terahertz wave range was studied under the influence of an external constant electric field. The transmission/absorption of THz radiation through a sample of the animal’s spinal cord was experimentally investigated. The refractive index of the sample was measured. Resonant absorption frequencies were observed. The nature of the transmitted THz pulse changes depending on the applied voltage, and nonlinear phenomena are observed; further studies are required to understand the nonlinear behavior of the nerve fiber system in the THz range.

In this work, the nonlinear properties of the animal's nerve fiber system in the THz wave range were studied, and mathematical modeling was performed. The results of the modeling were compared with the experimentally obtained data.

Methods and results. A sample of the white matter from a sheep’s spinal cord was taken as the nerve fiber system, and placed inside a polytetrafluoroethylene (PTFE) cuvette with a thickness of 100 μm and dimensions of 20 mm x 20 mm, as schematically shown in Fig. 1, similar with experimental setup implemented in [3] and [4]. The nerve fibers were aligned parallel to each other and to the walls of the cuvette. Two electrodes were positioned along the edges of the sample, parallel to the nerve fibers, ensuring proper electrical contact with the sample.

The experimental investigations were performed using a Menlo Systems LAC 1.550 time-domain terahertz (THz) spectrometer. The cuvette containing the sample was positioned in the path of the THz beam, and the THz pulses transmitted through the sample were recorded by the spectrometer's THz detector. The acquired data were processed using custom-developed software, resulting in the spectrum of the THz pulses transmitted through the sample and determining its parameters in the THz frequency range.

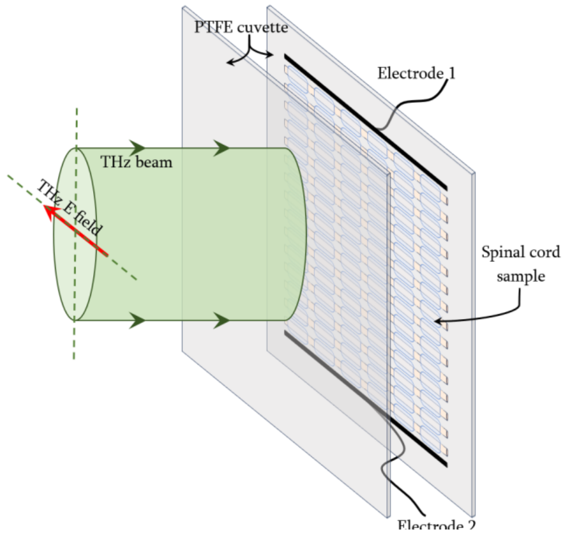

Fig. 1. Sketch of the spinal cord sample, with electrodes positioned inside a PTFE cuvette

Measurements were conducted under two conditions: with no voltage applied to the electrodes, and with a voltage of 100 V. The results of measurements show that parameters of different samples (absorption spectrum, refractive index), before voltage is applied to electrodes, show similar behaviour. It was also shown that, in the presence of the constant external voltage, the parameters of the samples change over time, and these changes are of a similar nature across different samples. The characteristic patterns of the time domain and power spectrum of the THz wave passing through the sample are presented in Fig. 2.

It can be clearly seen from Fig. 2 that in the presence of voltage, a nonlinear transformation of the transmitted signal occurred. Computer modeling was performed to provide a qualitative assessment of the nonlinearities.

The modeling was performed according to polynomial (1), through which the input signal is subjected to nonlinear transformation,

$$E_{out}(t) = a_1 E_{in}(t) + a_2 E_{in}{}^2(t) + a_3 E_{in}{}^3(t) + a_4 E_{in}{}^4(t) \quad (1),$$

where, E_{in} is the electric field of the THz pulse passed through the sample in the absence of external voltage, E_{out} is the transformed signal, and the a_i values are the coefficients of the corresponding polynomial terms. The spectrum of the E_{out} obtained as a result of the modeling was compared to the spectrum of the THz pulse transmitted through the sample under the influence of external constant voltage, recorded experimentally at different moments of time. The values of the a_i parameters were determined, for which the spectra obtained from the modeling were most similar to the experimentally obtained spectra of the THz pulses (Fig. 3).

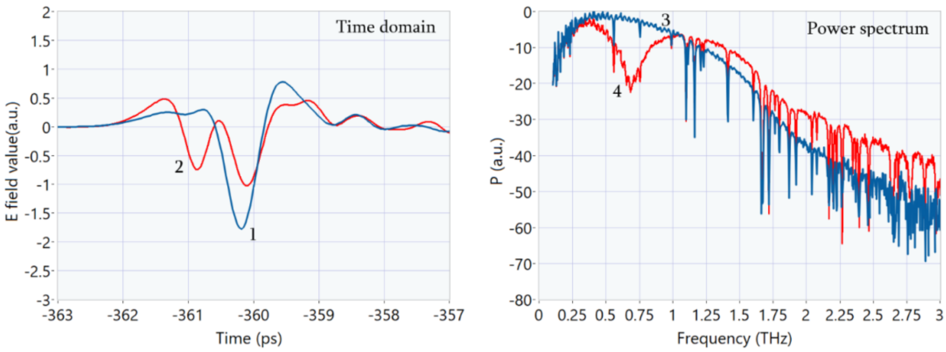

Fig. 2. Time domain (1) and power spectrum (3) waveforms of THz pulses passed through the sample before the application of voltage. Time domain (2) and power spectrum (4) waveforms of THz pulses passed through the sample 2 minutes after the application of voltage.

Discussion and conclusion. In Figure 3, curves 1 correspond to the spectrum of the THz wave passed through the sample before the external voltage was applied, it is provided as a reference waveform. Curves 2 and 3 represent the spectra of the THz wave in 0,5 and 2 minutes, respectively, after the voltage is applied to the sample. Curves 4 and 5 represent the results of the nonlinear transformation of THz pulse (curve 1), with the a_i values shown on the respective graphs. It can be noticed that along with the duration of voltage application, the coefficients of nonlinear terms (a_2, a_3, a_4) increase, while the coefficient of the linear term (a_1) decreases.

These results suggest that when external voltage is applied via electrodes, the nerve fiber system becomes a nonlinear system in the THz range with the nonlinearity increase depending on the duration of the applied voltage. Based on the structural characteristics of the Ranvier nodes, it can be assumed that upon voltage application, the ion channels in these nodes are excited and apparently become local nonlinear inhomogeneities in the nerve fiber system, which leads to the overall nonlinear behavior of the sample. The modeling results indicate that the spectrum of the nonlinearly transformated signal qualitatively resembles the spectrum of experimentally measured THz pulses.

The results of this research can help to understand the working principle of information propagation and exchange in neural systems in living organisms, as well as, complex processes taking place in central nervous system of living organisms.

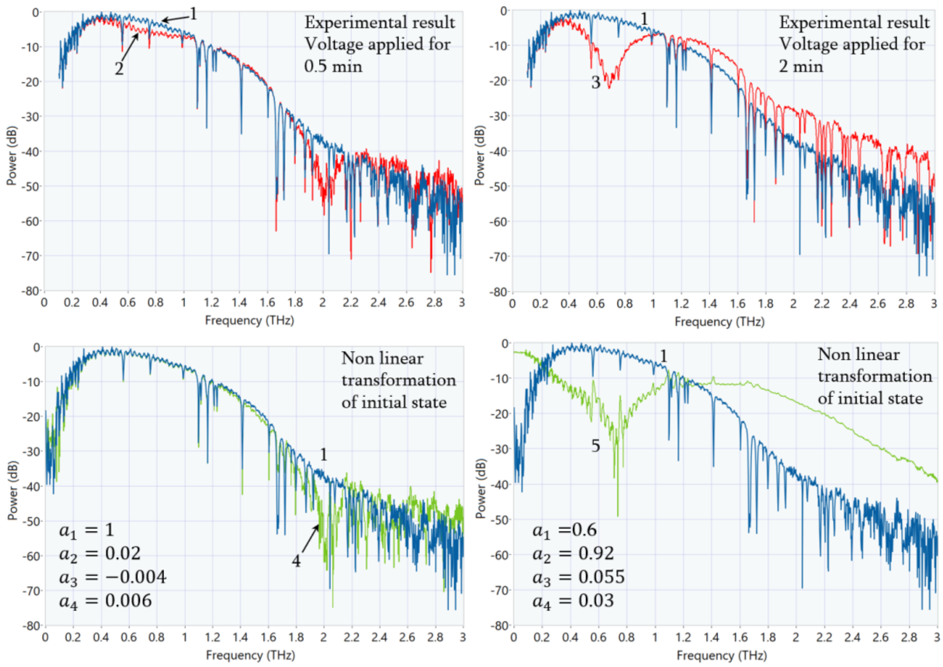

Fig. 3. Curve 1 – spectrum of the THz wave passed through the sample before the external voltage application. Curves 2 and 3 represent the spectra of the THz wave after 0,5 and 2 minutes, respectively, of applying the voltage to the sample. Curves 4 and 5 represent the results of the nonlinear transformation of THz pulse (curve 1), corresponding a_i values shown on the respective graphs.

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Տ.Ն. Հովհաննիսյան

Կենսաբանական նյարդաթելային համակարգի ոչ գծային հատկությունները տերահերցային սպեկտրալ տիրույթում

Այս աշխատանքում ուսումնասիրվել են կենդանու նյարդաթելային համակարգի ոչ գծային հատկությունները ՏՀց ալիքների տիրույթում, կատարվել է մաթեմատիկական մոդելավորում: Մոդելավորման արդյունքները համեմատվել են փորձնականորեն ստացված արդյունքների հետ:

Մոդելավորման արդյունքները ցույց են տալիս, որ ոչ գծային ձևափոխություններից հետո ստացված ազդանշանի սպեկտրը որակապես համապատասխանում է փորձնականորեն գրանցված ՏՀց իմպուլսների սպեկտրի հետ:

Т.Н. Оганесян

Нелинейные свойства биологической системы нервных волокон в терагерцовом диапазоне спектра

В данной работе были изучены нелинейные свойства системы нервных волокон животного в диапазоне терагерцовых волн, а также проведено математическое моделирование. Результаты моделирования были сопоставлены с экспериментально полученными данными.

Результаты моделирования показывают, что спектр нелинейно преобразованного сигнала качественно подобен спектру экспериментально измеренных терагерцовых импульсов.

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