Development of High-Frequency Measuring System for Ultrasonic Experimental Installation

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Abstract. This paper is devoted to the development of measurement system for an ultrasonic installation based on phase detection principle and allowing to measure relative sound velocity and attenuation changes in the frequency range of 30–300 MHz.

INTRODUCTION

The study of the structure of matter and the relative arrangement of atoms in molecules plays an important role in understanding the behavior of their reactivity, chemical activation in catalysis, electron-conformational interactions, the production of substances with specified properties, *etc*. One of the directions in the development of the theory of the structure of matter is associated with the rejection of complete separation the motions of electrons and nuclei in molecules and crystals in the adiabatic approximation; and with a more detailed account of their interaction by means of vibronic mixing of electronic states with nuclear displacements. This approach allows us to describe a multitude of phenomena known under the general name of the Jahn-Teller effect (JTE) which is an important mechanism of spontaneous symmetry breaking in molecular and solid-state systems which has far-reaching consequences for different fields, and it is related to a variety of applications in spectroscopy, stereochemistry and crystal chemistry, molecular and solid-state physics, and materials science.

The ultrasonic measuring system can be used to measure the dependence of the relative amplitude attenuation and the relative change in the speed of sound oscillations in solid states and molecular compounds, and calculating the physical constants of the samples on the basis of the measurement results. In particular, based on these data, it is possible to calculate the dependence of the relaxation time of Jahn-Teller centers on temperature, and their adiabatic potential, according to the algorithm described in [1]. The installation is constructed in a manner similar to that described in [2], but it has a simpler internal organization and requires a smaller number of measuring channels, due to the use of phase detection on a mixer instead of a quadrature one.

OPERATION SCHEME OF THE INSTALLATION

Functional scheme of the installation is shown on the Fig. 1. The measuring system functions in the following way. The electric high-frequency oscillations from the generator 1 are fed to the splitter 2, where they are divided into three channels. The channel leading to the frequency counter 16 allows to fix the frequency of oscillations and transfer it to the Personal Computer 15, which is used which is used to which is used to store and display files with measurement results. The channel leading directly to the mixer 10 is used as a reference signal when multiplying. The channel leading to the sample is equipped with a key 17 controlled by the microcontroller 14 and openable for short periods of time, forming radio pulses, which are then amplified by the power amplifier 3.

The conversion of the signal into mechanical oscillations and back is carried out using piezoelectric transducers 4, 6 fixed on the sample 5, which is placed into cryostat 7 which is used to smoothly change the temperature in the

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range 2–300 K. The temperature in the cryostat is regulated by the thermocontroller 8. After that the signal is amplified by the low noise amplifier 9. High-frequency noise is cut off with the low-pass filter 11. Oscilloscope 12 can be used for operating signal monitoring. ADC 13 is used for digitization of the signal. MCU 14 is used for signal transmission to the PC 15 and tuning of the high-frequency signal generator 1. The time of passage of the pulse through the sample is τ_0. The reflected pulses follow the first with a time interval of $2\tau_0$, with their amplitude decreasing exponentially. A single pulse passage gives a phase shift $\Phi = kl_0$, so the n-th pulse has a phase shift determined by the expression (1) with respect to the reference signal:

$$\Phi_n = kl_0(2n+1) = \frac{\omega}{v} l_0(2n+1), \tag{1}$$

where k is the wave number, l_0 is the length of the sample, and v is the speed of sound. Then the signal is amplified and the sample signal $B = B0 \cos(\omega t + Fn)$ is multiplied with the reference signal $A = A0\cos(\omega t)$ in the mixer 16. The signal resulting from the multiplication is described by the expression (2):

$$AB = \frac{1}{2} A_0 B_0 [cos\Phi_n + \cos(2\omega t + \Phi_n)]. \tag{2}$$

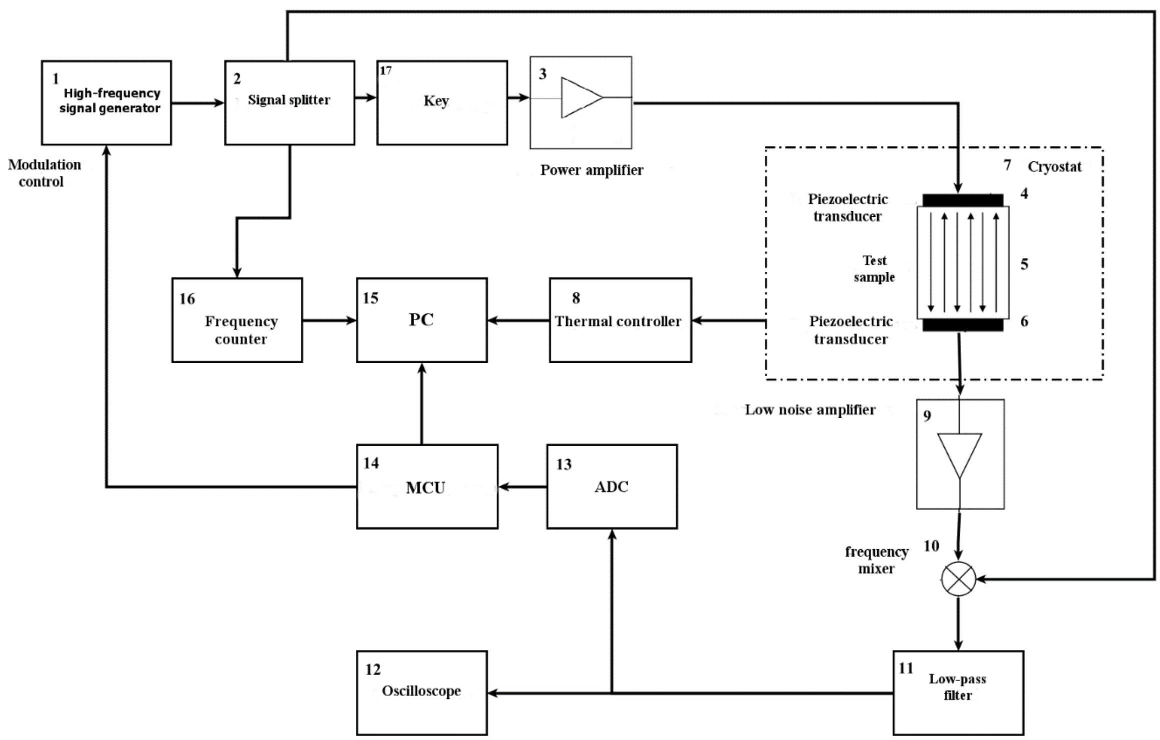

FIGURE 1. Schematic diagram of the measuring system

After passing the LPF, a signal of the form $\frac{1}{2} A_0 B_0 cos\Phi_n$ is obtained. Then, through a low-noise amplifier, the signal is fed to the ADC, digitized and read out by the MCU. The microcontroller acquires data on the amplitude of the signal and achieves its maximum, by adjusting the oscillator frequency, providing a zero phase shift between the signal passing directly into the mixer and the signal passing through the sample. The relative change in phase is given by (3):

$$\frac{\Delta\Phi_n}{\Phi_n} = \frac{\Delta\omega}{\omega} - \frac{\Delta v}{v} + \frac{\Delta l_0}{l_0}. \tag{3}$$

Thus, if the phase is constant, the change in frequency is directly proportional to the change in velocity, since the change in length, due to a change in temperature or magnetic field, is negligible compared to the change in velocity. Consequently, the relative change in speed is determined by the expression (4):

$$\frac{\Delta\omega}{\omega} = \frac{\Delta v}{v} \tag{4}$$

The amplitude of the signal passing through the sample is used to determine the absorption. For a known length of the sample, the absolute value of the speed of sound is defined as:

$$v = l_0 \frac{2n+1}{t} \tag{5}$$

The sample, together with the attached transducers, is immersed in a cryostat with helium gas and can be cooled to 3 K. Furthermore, linear heating is controlled by the thermocontroller in the process, which records changes in the speed and absorption of the ultrasonic wave as a function of the temperature. This scheme of measuring system construction has several useful qualities, which greatly facilitate the conduct of the experiment. So, due to the fact that piezoelectric converters are frequency-selective filters, and the sample significantly attenuates signals in the entire range, low noise values in the measuring path are provided.

OPERATING PRINCIPLE OF THE MEASURING SYSTEM

The operating principle of the measuring system is based on the balancing the frequency-tuned HF acoustic measuring bridge. In the measuring leg, the bridge contains piezoelectric transducers and a sample, with the reference arm of the reference signal entering the mixer. The balance is achieved by tuning the oscillator frequency with the help of MCU, as a result the phase in which the signal arrives from the sample changes, and, consequently, the amplitude of the signal at the input of the ADC, the code from which enters the MCU. The total phase balance corresponds to the maximum value of the signal at the mixer output. The change in the amplitude of the signal at the output of the mixer as a function of frequency is shown in Fig. 2.

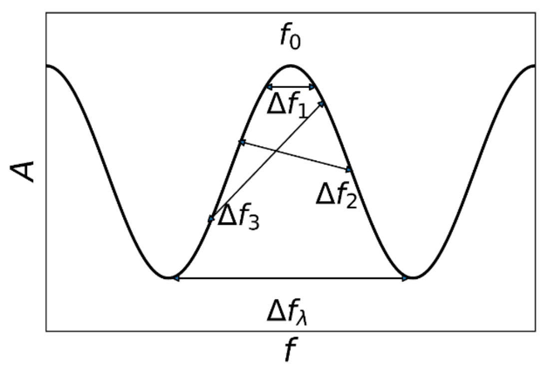

FIGURE 2. The change in the amplitude of the signal A at the output of the mixer as a function of the frequency *f*

The value of Δf_λ corresponds to the phase change in the measuring arm by 2π. For a sample length of the order of 1 cm and a sound velocity of $5 \cdot 10^5$ cm/s Δf_λ will be $5 \cdot 10^5$ Hz [3], thus at operating frequencies of the order of 10^8 Hz the phase change by 2π is provided by a relatively small change in frequency. On the key with the MCU, opening pulses of 10 ns–10 µs duration are given depending on the specific system settings. For the duration of the pulse, oscillations from the generator pass through the sample and multiply with the reference signal form a pulse of rectangular shape at the output of the mixer. Through the preset delay time from the moment the key is opened, the voltage amplitude is digitized with the help of the ADC and the code is written in the MCU. To maintain the output voltage at the maximum, and therefore maintain the minimum phase difference, the following algorithm is used:

– the fundamental frequency f_0 is selected;
– two series of measurements are carried out at frequencies $f_0 \pm \frac{\Delta f}{2}$;

– the measurement results are averaged over each of the series and compared, depending on the difference in the measurements between the series, one of the two solutions can be adopted:
1) if the difference is less than the set error value, f_0 is taken as the balance frequency, the amplitude of the signal is repeatedly measured at the balance frequency, its results are averaged, the values of the balance frequency and the amplitude of the signal are sent to the PC;
2) if the difference is greater than the set error value, a decision is made to change f_0 in order to reduce the modulus of the difference, i.e. at positive values of the difference (Δf_2) f_0 decreases, and for negative values (Δf_3) it increases. Thus, a negative feedback loop minimizing the magnitude of the phase difference is created.

REQUIREMENTS AND REALIZATION OF THE MEASURING SYSTEM

As a requirement for the measuring system, the frequency range of the signal supplied from the generator to the sample was determined: 30-300 MHz. After LPF it was supposed to receive pulses close to rectangular ones with minimum duration of the front and decay of about 50 ns, in order to accurately measure the pulse amplitude, it was required to sample the voltage in less than 10 ns at a certain section of the plane vertex of the pulse, suppressing frequencies above twice the minimum frequency of the signal from the generator coming from the mixer *i.e.* frequencies above 60 MHz. Also, it was necessary to provide high gain factors for the signal power supplied to the sample, and low noise values when amplifying the signal from the sample.

To implement the measuring system, the following components were used:

– Signal splitter - ZFSC-3-4+ [4].
– Key - HMC194AMS8 [5].
– Attenuator - HMC542BLP4E [6].
– Power amplifier - HMC1099 [7].
– Low-noise amplifier - TQP3M90 [8].
– Frequency mixer - ZFM-4+ [9].
– ADC - AD9233 [10].
– ADC driver AD8352 [11].
– MCU - STM32F429ZI [12].

OBTAINED RESULTS

As a result of the work the measuring system was designed and created. At this point, the installation is at the debugging stage, the first measurements are taken. Results of these measurements are shown in Fig. 3. Further we plan to improve the characteristics of the device and a signal processing algorithm.

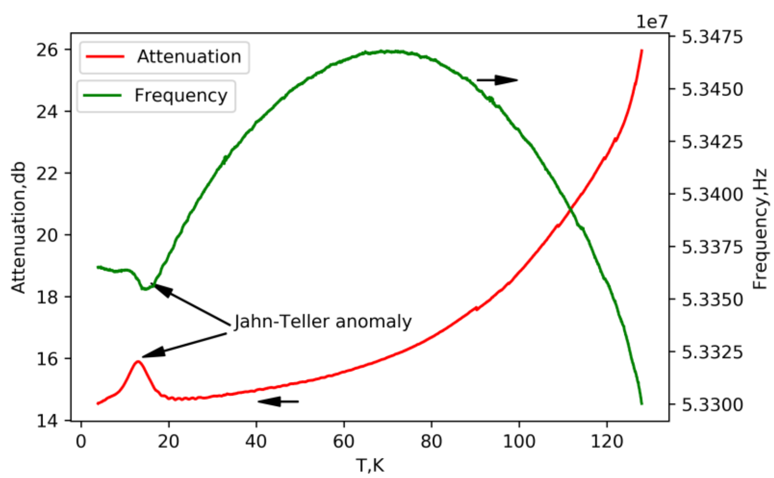

FIGURE 3. Dependence of absorption and frequency of an ultrasonic wave on temperature, ZnSe:Ni, shear wave, polarization [001]

CONCLUSIONS

The purpose of this work was to construct an installation for high frequency acoustical measurements. Within the framework of this work set goals were achieved, so that, the installation for measurements of absorption and frequency of an ultrasonic wave dependences from temperature changes was constructed using the principles described in mentioned above literature [1] and also basing on the modern improvements. The following vicious changes were made: quadrature detection was used, which made it possible to reduce the number of measuring channels, since it became possible to simultaneously record changes in the relative frequency and amplitude of the signal.

As it can be seen from the work, the installation is constructed and the dependence of absorption and frequency of an ultrasonic wave on temperature was obtained. These dependencies clearly coincide in form with ones mentioned in literature [1] and Jahn-Teller anomaly could be studied.

To conclude, this article proves the possibility of constructing the installation for measuring dependency of acoustical properties from temperature within the solid body which can be used to determine energy curves of Jahn Teller centers according with procedure described in [2]. Also, this installation could be used as a part of a laboratory complex for solid-state physics studying in UrFU.

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