# BASIC PRINCIPLES OF THERMO-ACOUSTIC ENERGY AND TEMPORAL PROFILE DETECTION OF MICROWAVE PULSES


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Basic principles of a thermo-acoustic method developed for the detection of powerful microwave pulses of nanosecond duration are discussed. A proposed method is based on the registration of acoustic pulse profile originated from the thermal expansion of the volume where microwave energy was absorbed. The amplitude of excited acoustic transient is proportional to absorbed microwave energy and its temporal profile resembles one of a microwave pulse when certain conditions are satisfied. The optimal regimes of microwave pulse energy detection and sensitivity of acoustic transient registration with piezo-transducer are discussed. It was demonstrated that profile of a microwave pulse could be detected with temporal resolution of 1 – 3 nanosecond.



*PACS number:* 29.17.+w


## 1 INTRODUCTION

A problem of wave profile detection of microwave pulses and measurement of their energy is of great importance in designing of high power relativistic microwave generators that utilize accelerators as a source of injecting electrons. A moment of the microwave pulse production is coincided with high level electromagnetic noise originated from instantaneous discharge of a reservoir capacitor [1]. The specific feature of microwave generator with electron accelerator is a low repetition period of pulses therefore one needs to provide measurements of particular pulse parameters in a one-sequence regime.

The vacuum diodes could be used for detection of microwave pulse energy but their application is limited for wavelengths greater than 10 cm due to resonance properties of diodes [2]. Conventional calorimetric devices are designed for energy W>100 mJ and their sensitivity is not enough for measuring of pulses with energies of several millijoules. Semiconductor detectors with hot carries utilizing effect of bulk detection are used for registration of the ns-pulse profiles. Unfortunately they are complex in application and liquid nitrogen is needed for their function.

We propose to utilize thermo-acoustic effect [3] for development of new detectors of the microwave pulses. Similar devices are already employed for the registration of laser pulses in visual and infrared spectrum range [4]. At certain conditions acoustic pulse originated from thermo-acoustic conversion could completely resemble initial microwave pulse profile.

## 2 BASIC PRINCIPALS OF THE THERMO-ACOUSTIC DETECTION

Let us consider a microwave radiation falling on a boundary of two media (Fig. 1). Microwave radiation is propagated through the medium 1, which is transparent for electromagnetic radiation of millimeter wavelength range. At the boundary part of falling energy $W_i$ is reflected, and another part passes into absorber: $W_a = (1 - R)W_i$, where $R$ is the coefficient of energy reflection.

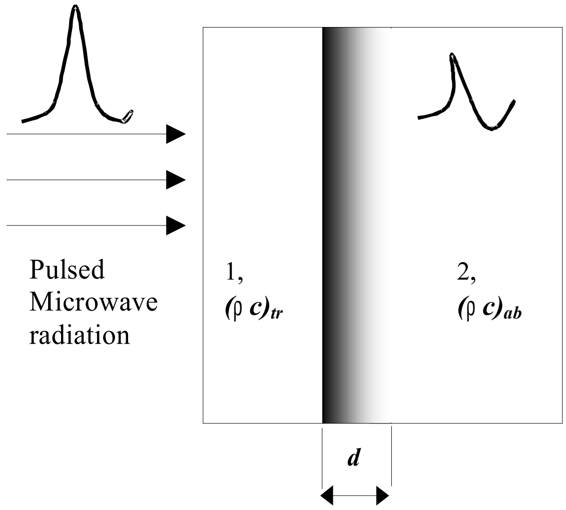


*Fig. 1. Thermal mechanism of sound generation by microwave pulse.*

Illumination of the absorbing layer by a microwave pulse with short duration results in instantaneous heat deposition inside absorber layer of a *d*-thickness. Subsequent thermal expansion of a layer produces acoustic waves that propagate from the absorber surface. We will consider two cases: rigid and free boundary condition. When acoustic impedance of the transparent medium exceeds one of the absorbing medium: $(\rho c)_{tr} >> (\rho c)_{ab}$ the rigid boundary conditions are satisfied. Here $\rho$ is the density of medium, $c$ is the speed of sound. In the opposite case $(\rho c)_{tr} << (\rho c)_{ab}$ it is said that free boundary conditions have place. We will consider in detail the first case as most important for waveform measurement application. When the microwave pulse has a Gaussian envelop $f(t) = (\pi)^{1/2} \exp\left[-(t/\tau_R)^2\right]$ the thermoacoustic pulse can be expressed in the following analytical form [3]:

$$p(\tau) = \frac{c_0^2 \beta \alpha E_a}{4c_p} \exp\left[\left(\frac{\alpha c_0 \tau}{2}\right)^2\right]\left\{\exp(\alpha c_0 \tau)\left[1 - \Phi\left(\frac{\tau}{\tau_R} + \frac{\alpha c_0 \tau}{2}\right)\right] + \exp(\alpha c_0 \tau)\left[1 + \Phi\left(\frac{\tau}{\tau_R} - \frac{\alpha c_0 \tau}{2}\right)\right]\right\} \quad (1)$$

where $\alpha$ is the coefficient of microwave absorption, $c_0$ is the speed of sound in absorbing media, $\beta$ is the thermal coefficient of volume expansion, $c_p$ is the specific heat, $\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-x^2)dx$ is the error function. The expression (1) shows that acoustic pressure pulse in the case of rigid boundary condition generation has a form of a unipolar symmetrical pulse of compression. We will consider two practically interesting cases.

**1.** When duration of a microwave pulse is small compared to time of sound propagation through the absorption layer $\tau_R << (\alpha c_0)^{-1}$, then the acoustic pulse profile is completely defined by absorption coefficient of microwave radiation and does not depend on the waveform of microwave pulse. This phenomenon is served as a base for the thermoacoustical spectroscopy of material. Measuring of temporal profile of the thermoacoustic pulse provides information on a spatial distribution of microwave absorption coefficient inside absorbing media. This idea is employed in a new system breast cancer diagnostics where light absorption coefficient at 1 μ m wavelength is measured from thermoacoustic pulse waveform [4].

**2.** When microwave radiation is absorbed in a very thin layer, i.e. a condition $\tau_R >> (\alpha c_0)^{-1}$ is satisfied the resulted thermoacoustic pulse profile is completely identical to the initial microwave pulse. One can estimate that for the 5-ns microwave pulse the length of absorption should be less then 1 micrometer: $\frac{1}{\alpha} \le 1\mu m$. The conductive materials should be employed as absorbers of microwave energy. In a conductive material with a conductivity $\sigma$ the wave with frequency $f$ is absorbed at the depth of a skin layer: $d = (\pi f \mu \mu_0 \sigma)^{-1/2}$, where $\mu$ is the magnetic conductivity, $\mu_0$ is the magnetic constant ($\mu_0 = 4\pi \cdot 10^{-7}$ H/m). The depth of a skin layer for different materials is presented in Table 1. It is demonstrated that perfectly conductive metals Al and Cu could be employed for the thermoacoustic conversion of microwave energy to the acoustic one.

Table 1. Depth of a skin layer for metals and water at 8-mm wavelength

| Material | Al | Hg | Cu | $H_2O$ | $H_2O$ salted |
|---|---|---|---|---|---|
| σ, $10^7$ (Ohm·m) | 3.54 | 0.104 | 5.8 | | |
| *d*,μm | 0.44 | 2.6 | 0.34 | 400 | 120 |

The peak pressure of the thermoacoustic pulse is defined by thermal properties of absorbing medium and quantity of absorbing energy:

$$p_{ac} = \frac{\beta c_0^2 \alpha E_a}{2c_p} = 0.5\Gamma \alpha E_a, \quad (2)$$

where $E_a$ is the surface density of microwave energy at the boundary of the absorbing medium. The parameter $\Gamma = \beta c_0^2 / c_p$ defines the efficiency of thermoacoustic conversion in deferent media. The value of this parameter in some media is presented in Table 2. Energy at the boundary of absorbing media is defined by the electric impedance ratio of transparent and absorbing media. At boundary of dielectric – conductor the transmission coefficient at normal wave incidence can be defined as: $T = (16\pi\varepsilon f/\sigma)^{1/2}$. This coefficient is small for metals, therefore the portion of energy transmitted and absorbed in metal is also small: $E_a = TE_i$. Transmission coefficients at 8-mm wavelength for conductors are presented in Table 2.

Table 2.

| Material | Al | Hg | $H_2O$ |
|---|---|---|---|
| Γ | 2.1 | 2.7 | 0.11 |
| T, % (f=37.5 GHz) | 0.71 | 1.3 | |

Using formula (2) one can estimate that the peak pressure amplitude of acoustic pulse excited in aluminum with microwave pulse of 1-mJ energy, illuminating 3-cm² surface can reached $P_{ac}$ = 0.5 bar.

## 3 MEASUREMENT OF MICROWAVE PULSE ENERGY

Amplitude spectrum of the acoustic pulse excited in absorbing medium can be expressed in the following form [3]:

$$F_r(\omega) = C_1 \frac{\alpha^2}{\alpha^2 + \omega^2 / c_0^2} \tilde{f}(\omega), \quad (3)$$

where $\tilde{f}(\omega) = (2\pi)^{-1} \int_{-\infty}^{\infty} f(t)\exp(i\omega t)dt$ is the spectrum amplitude of the microwave pulse envelop, $C_1$ is the constant. In the low frequency range $\omega << 2\pi/\tau_R$ the spectrum amplitude the microwave pulse envelop is practically constant $\tilde{f}(\omega) \approx (2\pi)^{-1} \int_{-\infty}^{\infty} f(t)dt = \tilde{f}(0)$ and it is defined by absorbed surface density of energy $E_a = I_a \int_{-\infty}^{\infty} f(t)dt$, where $I_a$ is the intensity of radiation at the boundary. The amplitude of low frequency components of thermoacoustic pulse is also independent of frequency. It can be shown that in 3-demensional case when finite dimensions of a microwave beam and absorbing volume are taken into account the low frequency components of thermoacoustic transient are proportional to a total absorbing energy. Therefore the energy could be measured by detection of signal produced with thermoacoustic pulses at low frequency range.

## 4 EXPERIMENTAL SET UP

Schematic diagram of the experimental set up for detection of microwave pulse profile is shown in Fig. 2. The aluminum layer of 2-mm thickness 2 was used as absorber of microwave radiation of 8-mm wavelength. Quarts glass plate of 5-mm thickness or ceramic 22XC was employed as microwave transparent materials. The transparent plate 1 covered the absorber; both boundary surfaces of transparent and absorbing plates were carefully polished and slightly moistened to provide perfect acoustic contact. The microwave radiation was directed on the surface of thermoacoustic converter. Duration of microwave pulse was less then duration of discharge current pulse which profile is shown in Fig. 3. It is seen that duration of discharge current pulse measured at half level of peak value was 7 ns, therefore it was expected that duration of excited microwave pulse should be about 5 ns. Acoustic pulse excited in absorbing aluminum layer propagated through water layer 3 of 2.2-mm thickness. Wide-band (1–100 MHz) ultrasonic transducer made of $LiNbO_3$ crystal 4 was used for detection of acoustic pulse. Transducer operated in a short circuit mode: electric charge originated due to acoustic instantaneous pressure was measured on the electrodes installed on the back surface of piezoelectric crystal. The thickness of crystal was larger that a spatial length of detected acoustic pulse. Output of transducer was loaded on 50-Ohm resistor to provide quick discharge of transducer self-capacitance. A transducer signal was amplified with wide-band amplifier 5 and recorded by digital oscilloscope 6 (Tektronix THS 220). The sensitivity of ultrasonic transducer 30 mV/bar was comparatively small. It was expected that maximum signal should be about 15 mV. Time of acoustic pulse arrival was delayed relatively microwave pulse on time of sound propagation in aluminum layer, water and ultrasonic transducer. Total delay time in our scheme was 2.7 μs. The noise level originated due to capacitor discharge at the moment of microwave pulse generation was about tens Volts and it dropped quickly with time. Unfortunately it exceeded 40 mV after 2.7-μs time interval, therefore it was impossible to make a direct registration of the thermoacoustic pulse in the employed scheme. But we recorded the reverberations that appeared at time greater than 7-10 μs that served as indirect evidence of a principal efficiency of proposed method.

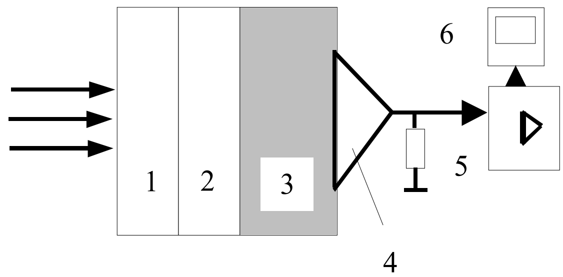


*Fig. 2. Experimental set up.*

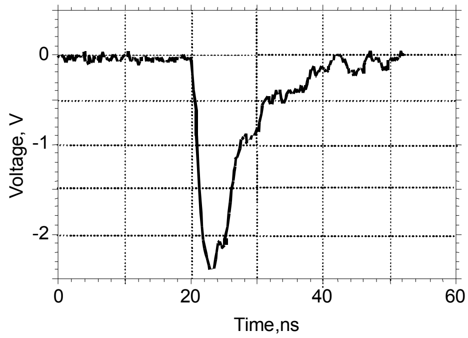


*Fig. 3. Profile of a capacitor discharge current.*

This work was supported by RFBR grant # 01-02-17344.

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