Acoustic Detector for Registration of Powerful Microwave Pulses[1]

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Abstract – General concept of operation and design of the uncooled acoustic detector for registration of powerful microwave pulses of nano and subnanosecond duration is described. The operation of the detector is based on thermoacoustic effect. Waveform of an acoustic transient excited in thin absorbing layer replicates the waveform of the microwave pulse. Excitation the acoustic transient was performed in the stratified structure quartz – aluminum film – liquid where the film thickness was varied in a range of 1.5 – 500 nm. Coefficient of microwave absorption in the aluminum films had maximum of 60 % for 2 – 2.5 nm film thickness. Wideband acoustic transducer with PVDF film as a sensitive element was used for acoustic transient's detection. In linear regime of generation the detected waveform had a form of unipolar pulse of 18 ns duration. The most effective thermoacoustic transformation of energy was detected for 3.5 nm film thickness.

1. Introduction

Registration of temporal profile of microwave pulses is actual in the conditions of strong electromagnetic noise resulted from intensive electron beams in high-current accelerators, used in modern microwave generators [1,2]. The complicity of registration of the microwave pulses is defined by their high power levels, shot duration and wideband frequency spectrum. It is also necessary to take into account a specificity of microwave generator operation including regime of singular pulse when the waveform and pulse energy should be measured in one cycle.

The known detectors of power and energy of the single microwave pulses are vacuum diodes, semiconductor detectors on hot carriers, calorimetric meter of pulse energy [3]. The vacuum diode can be employed only for wavelengths exceeded 10 cm where its resonance properties are not significant. The calorimetric meters are used for registration of pulses with high energy in one pulse. High-sensitive calorimeters for registration of the pulses with energy in a range 0.01 – 0.1 J are very technically complex and expensive. Application of the detectors on the hot carriers based on effect of volume detection requires cooling to temperatures of liquid nitrogen.

We propose to employ thermoacoustic effect [4] for design and manufacturing of a principally novel detector of microwave radiation. The similar devices are already employed for registration of laser pulses in visible and infrared ranges [4]. At certain conditions acoustic pulse excited in course of thermoacoustic transformation may completely replicate a temporal waveform of microwave pulse.

2. Design of the detector

The main parts of the detector are schematically presented in Fig. 1.

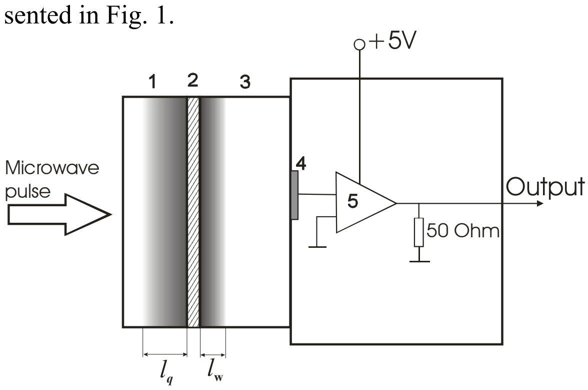

Fig.1. Schematic diagram of the thermoacostic detector. 1 – quartz substrate, 2 - aluminum film deposited on the quartz, 3 – layer of liquid, 4 piezoelectric transducer, 5 – wideband preamplifier. The areas of heat diffusion in quartz and liquid during microwave pulse are schematically shown with grey color.

The microwave pulse was directed on aluminum film 2 sputtered on the surface of quartz substrate 1. Aluminum film was in a contact with layer of liquid 3 with thickness varied in a range of several millimeters. Energy conversion of a microwave pulse to acoustic transient took place within aluminum film and layer of liquid contacted with it. The acoustic pulse passed through the liquid layer and was detected with wideband piezoelectric transducer 4. The signal detected by acoustic transducer by amplified by the preamplifier 5 located in the vicinity of transducer in the same case. The input capacitance of the preamplifier did not exceed 2 pF and its noise level was about several µV in frequency range 30 kHz – 100 MHz. The output resistance of the preamplifier was 50 Ohm to allow transferring the short pulse through a long coaxial cable with 50-Ohm wave impedance.

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A choice of thin metallic films for a detector design was defined by their ability to absorb high-frequency electromagnetic radiation. It was experimentally demonstrated [5] that absorption of electromagnetic continuous radiation with 8-mm wavelength incident on the layered structure quartz substrate – aluminum film was 49% of overall incident energy. Maximum of absorption coefficient was observed for the film thickness 2.0 – 2.5 nm. It was of principal importance that reflection coefficient at the same time did not exceed 44%.

3. Process of thermoacoustical energy conversion

Description of generation of an acoustic signal in the structure presented in Fig.1 can be divided in two steps. Absorption of electromagnetic energy within aluminum film results in its heating. As the film thickness is about several nm, the released heat quickly diffuses in surrounding liquid and quartz substrate. Characteristic time of thermo-diffusivity from a plane layer of the *d*-thickness can be estimated as $t_{Al} = \dfrac{d^2}{4\chi_{Al}}$, where χ_{Al} is the coefficient of thermal diffusivity of aluminum. For the film of 2- nm thickness time of thermodiffusivity can be assessed as 10 fs what is several orders less than pulse duration (10 ns). Therefore it can be considered that heat leaves the film practically instantly. Quartz and liquid are heated as due to direct absorption of microwave radiation as due to heat diffusivity from aluminum film. Transmission coefficient of the aluminum film with thickness exceeded 2 nm is less than 7 % and it is reduced with thickness increasing. As a result, liquid heating due to direct absorption of microwave radiation is small compared to heat diffusion from aluminum film. We used distilled water in the experiments, therefore thermo-physical and acoustical parameters of water will be used in subsequent calculations. In water heat propagates the distance of $l_w = 2\sqrt{\chi_w \tau_p}$ during the microwave pulse duration τ_p, where χ_w is the coefficient of thermo-diffusivity of water. Time of sound propagation across the heated layer can be estimated as $\tau_w = l_w / c_w$, where c_w is the speed of sound in water at room temperature. The thickness of heated layer is about 75 nm and time of sound propagation across this layer is 50 ps for microwave pulse duration of 10 ns. The heated layer is expanded and as a result the acoustic pulse is induced. The duration of a microwave pulse significantly exceeds time of sound propagation across the heated layer, therefore the temporal profile of the induced acoustic pulse replicates waveform of microwave pulse [4]. The similar calculations performed for quartz showed the following results: l_q = 185 nm, τ_q = 120 ps. A flux of heat from aluminum film in quartz substrate almost 2 times higher the heat flux in water due to enhanced thermodiffusivity of quartz.

Peak acoustic pressure in linear regime when temperature increasing does not exceed 10 ^{0}C can be evaluated with following expression:

$$p'_a = \frac{\beta c^2}{2C_p}\frac{AE_{in}}{lS}, \tag{1}$$

where β is the coefficient of thermal expansion, c is the speed of sound, C_p is the specific heat at a constant pressure, A is the coefficient of microwave absorption, E_{in} is the energy of incident wave, l is the thickness of heated layer, S is the radiated surface. Combination of thermo-physical parameters $\dfrac{\beta c^2}{C_p}$ characterizes efficiency of thermoacoustical energy conversion. This value for water 4 times exceeds one for quartz. In addition, the thickness of heated layer in water 2 times less than in quartz. Therefore it can be considered that water plays the main role in thermoacoustical energy conversion in the proposed design.

4. Experimental studies

Experimental verification of the proposed scheme of microwave pulse registration was performed with use of relativistic generator of the surface wave of a millimeter range. Electron mini-accelerator designed on the base of conventional Roentgen device was used as an electron injector. A ring-type cathode with explosive emission provided pulses of current with amplitude of 0.5 – 0.7 kA and accelerating voltage of about 150 kV and 5-ns duration measured at half-amplitude level. A beam of electrons interacted with decelerating system of diaphragm waveguide type. The π-type vibration regime in the vicinity of high frequency band of transparency of the decelerating system was employed. It can be located up to 30 periods of diaphragm inclusions in the space of interaction. Variation of the number of inclusions allowed us to optimize a power of output radiation and change a directivity pattern of the beam. This set up provided pulses of microwave radiation with 2-MW power at wavelength of 8 mm. Pulse energy was about 1 mJ. The waveform of microwave pulse registered with detector on the hot carriers is shown in Fig.2. Duration of a microwave pulse measured at half of peak value was about 5.2 ± 0.4 ns. It was defined by duration of the current pulse. Microwave pulse was radiated in air and directed with metallic cone on the quartz substrate of the thermoacoustic detector. Input diameter of the cone (35 mm) corresponded to the size of output diaphragm of the microwave generator; output diameter of the cone (20 mm) was equaled to diameter of the quartz substrate. Application of the cone allowed us to enhance a density of energy on the surface of aluminum film and thereby increase acoustic pulse amplitude.

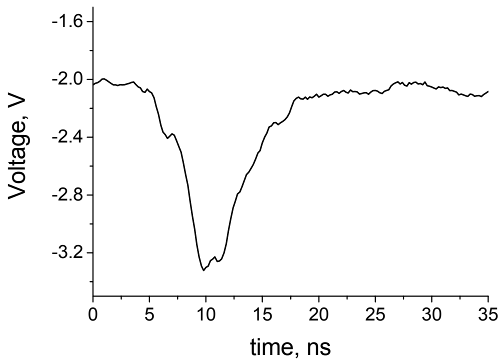

Fig. 2. Waveform of the microwave pulse measured with the detector on hot carriers.

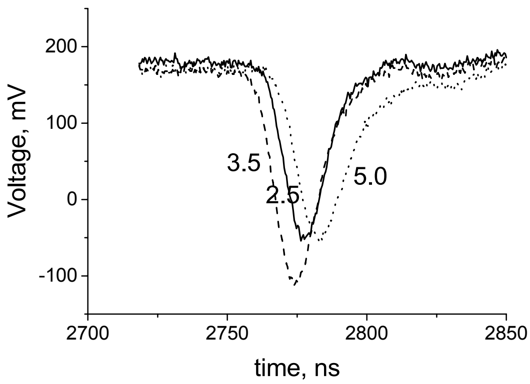

Fig. 3. Profiles of the acoustic pulses measured with different aluminum film thickness. Numbers near the curves correspond to aluminum film thickness in nanometers.

Aluminum film was in a contact with distilled water of 4-mm thickness. This layer of water provided 2.67 -µs time delay of the acoustic pulse that in turn, allowed us to avoid strong electric noise in the moment of microwave pulse generation. From the other side the water layer of such thickness practically did not influence on a temporal profile of the acoustic pulse due to small attenuation of ultrasound in water in a frequency range of the detected acoustic pulse. For detection of short acoustic pulse we used a piezoelectric PVDF film of 28 µm attached to polymer backing with acoustic impedance close to the impedance of the PVDF film. This detector was able to register acoustic signals in a frequency range about 50 MHz with sensitivity of 5 µV/Pa defined by the piezoelectric parameters of the film. The capacitance of the acoustic detector was about several pF therefore we used preamplifier located in the same case to reduce signal attenuation and provide transfer of the signal through a long (about 10 m) coaxial cable with 50-Ohm wave resistance. Signal of the detector was registered with digital Tektronix 3032 oscilloscope synchronized by a pulse of current from the microwave generator.

Profiles of the acoustic pulses measured with different aluminum film thickness are presented in Fig. 3. The acoustic signals had form of unipolar pulse with duration of 18±2 ns measured at half amplitude. Unipolarity of the pulse is resulted from the fact that water surface where the thermoacoustic energy conversion takes place is contacted with solid body which acoustic impedance significantly higher than in water. Limited frequency bandwidth of acoustic detector did not allow reproducing the temporal microwave profile presented in Fig. 2. Front duration of the acoustic pulse of 20 ns corresponds to frequency bandwidth of the detector equaled to 50 MHz. Experiments were performed with aluminum films with thicknesses 1 – 10 nm. Maximum efficiency of thermoacoustic conversion was observed in the 3.5 –nm film. Peak pressure of the acoustic signal for this film was about 0.5 bar which is in agreement with estimations obtained from (1).

5. Conclusions

Experimental verification of main parameters of new thermoacoustic detector of microwave pulses of nanosecond duration was performed. A principle of operation of the detector is based on a process of microwave energy conversion to acoustic wave in thin metallic film contacted with liquid. The detected acoustic waveform was in a form of the unipolar pulse of 18-ns duration. The most effective energy conversion was obtained for the film thickness of 3.5 nm. The currently designed detector can be used for registration of microwave pulse profiles with duration exceeded 20 ns. Energy of pulse should be 0.2 mJ or higher. To enhance operation speed of proposed detector it is necessary to employ acoustic transducers with wider frequency bandwidth. In particular, the employment of 9-µm piezoelectric PVDF film will allow reproducing the 5-ns pulse waveform correctly.

References

[1]. Mesyats G.A., *Generation of high power nanosecond pulses.* M., Sov.Radio, 1974.

[2]. Vdovin V.A., Korjenevskiy A.V., Cherepenin V.A., Izv. RAN, Physics, 1997, v.61, no.12, 2276.

[3]. Belousov V.I., Zelentsov V.I., Ofitserov M.M., *Relativistic microwave electronics*. Gorkiy, IPF RAN, 1979, pp. 275-292.

[4]. Gusev V.E., Karabutov A.A., *Laser optoacoustics,* M., Nauka, 1991, 304.

[5]. Andreev V.G., Vdovin V.A., Voronov P.S., Technical Physics Letters, 2003, v.29, 953-955. http://dx.doi.org/10.1134/1.1631376