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Thermophysical and mechanical properties of active membranes for photoacoustic generators of forced acoustic oscillations

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Thermophysical and mechanical properties of active membranes for photoacoustic generators of forced acoustic waves are studied. Dependencies of photoacoustic generators output characteristics versus active membranes parameters are found out for different heat power densities in the case of forced acoustic oscillations.

Keywords: Photoacoustic generator, forced acoustic oscillations, linear oscillations, full width at half maximum, active membrane.

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Systems of technical and biomedical ultrasonic diagnostics require an imaging technique (for example, photoacoustic imaging [1,2] or terahertz imaging [3,4]) with high spatial resolution, therefore there is a trend to use broadband and ultrabroadband sounding acoustic signals. With the use of these signals, the spatial resolution is increased by time-frequency base of sounding signal remove [5]. Also, important requirements to ultrasound sources for imaging are their compactness and flexibility (the possibility to change type of the signal) [6].

Very promising ultrasound sources for the purpose of acoustic imaging are photoacoustic generators [7–9]. Fiber optic ultrasound transmitters possess a number of benefits: wide bandwidth all-dielectric design, low weight and size [2,10].

For an absorptive structure exposed to intensity-modulated laser beam, when the characteristic time of absorption comes out to be considerably lower than the modulation period, a change in its size causes a forced acoustic oscillation with the frequency defined by the laser beam modulation frequency [9,10]. It is suggested to implement imaging with remove photoacoustic generators based on forced oscillations, because the bandwidth of the generated signal is completely defined by the laser beam modulation [8,10,11].

An actual task is to study thermophysical and mechanical properties of active membranes (in other words - absorptive structures) of photoacoustic generators based on forced acoustic oscillations. Therefore, the purpose of this work is to determine the interrelation between the input parameters of active membranes (radius and thickness) and amplitude as well as bandwidth of output acoustic oscillations.

In this work, the following design is studied laser emission is fed to active membrane without physical contact (in this case the active membrane can be manufactured separately from optic fibers using any suitable and available technology). The photoacoustic generator is implemented as follows: at the first stage the absorptive structures, for example, active membranes based on absorptive particles within a polymer matrix or Tamm structures are attached to a board with the holes. Bonding with special organic compounds is typically used jointly with low temperature co-fired ceramic board. This allows the generator to work in severe operating conditions (high temperature, radiation, strong microwave emission) [12]. Then the absorptive structure is adjusted with optic fibers, that allows to couple more than 80−90% of optical power. This generator is shown schematically in Fig. 1, *a*.

The fastest and the most effective photoacoustic generators are built on the basis of nanostructures. With the same thickness of the absorptive layer, nanostructures allow remove higher (up to an order of magnitude) absorption coefficient as compared to volume optical absorbers. Due to ultimately small dimensions of nanostructures in comparison with polymer matrix, thermal and mechanical properties of the active layer are almost fully defined by parameters of the polymer. Since wavelength of the excited acoustic oscillation is considerably higher than nanostructure dimensions, it is reasonable to use the approximation of isotropic membrane and homogeneous heat release for theoretical studies [13]. Polymers providing the fastest heat transfer as well as the strongest thermal expansion are preferable for active membrane matrix. A promising matrix is polydimethylsiloxane [14]. This matrix allows for obtaining high thermal-expansion coefficient and improvement of photoacoustic conversion efficiency by four orders of magnitude [13,14].

At the first stage of simulation, a disc structure remove with thermophysical and mechanical parameters corresponding to polydimethylsiloxane is created. Model of the studied active membrane of photoacoustic generator is shown in Fig. 1, *b*. A short wideband optical pulse with a high amplitude is used as a sounding signal for the simulation in time domain; the power of heat release is set depending on time. Fig. 2, *a* shows volume density of heat release, as well as offset of the photoacoustic generator active membrane center normalized to maximum values versus time. A volume density of heat release [W/m^3] is defined in the form of Gaussian pulse, the membrane offset remove is lagging [m], the process of cooling is slow.

The dependence of heat release volume power is dived into N steps (typically $N > 2^8$), and at each time step the heat release problem is solved for the whole structure. In this case after each of N three-dimensional temperature distributions is calculated, the problem of structural analysis is solved to obtain three-dimensional distribution of stress, pressure in the structure. The initial structure is formed for the next time step. The simulation is carried out in time domain; while the analysis of results is interpreted in time and frequency domains [6]. Frequency response of a photoacoustic transducer can be estimated as a ratio between the power spectral density of heat release and the membrane center offset. Membrane offset is proportional to the power spectral density of acoustic pressure:

$$S(f) = \left| F\left\{ \frac{P(t)}{P_{\max}} \right\} \right|^2 \left| F\left\{ \frac{\Delta z(t)}{h} \right\} \right|^{-2}, \qquad (1)$$

where $P(t)$ — heat release power as a function of time that achieves its maximum $P_{\max}$; $\Delta z(t)$ — membrane center offset as a function of time calculated as a result of solution of a number of structural analysis problems for the active membrane of photoacoustic generator; F — Fourier-transform operator; h — thickness of the active membrane.

For each set of active membrane geometric dimensions of N three-dimensional distributions of mechanical offsets,

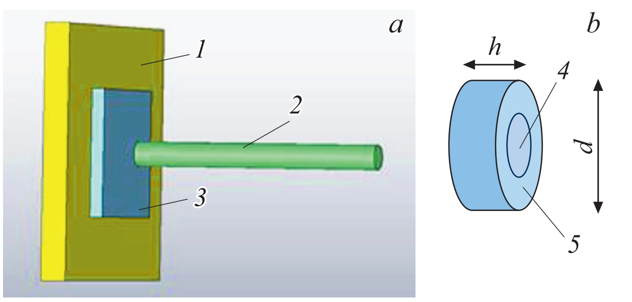

Figure 1. Schematic illustration of photoacoustic generator (*a*) and a model of the studied active membrane of photoacoustic generator (*b*). *1* — board, *2*— optic fiber, *3* — absorptive layer, *4* — movable part of the membrane where the heat is released, *5* — fixed ring (surface of the fixed ring in the board plane — heat exchange surface — occupies 10% of the current radius of structure). *h* — membrane thickness, *d* — membrane diameter.

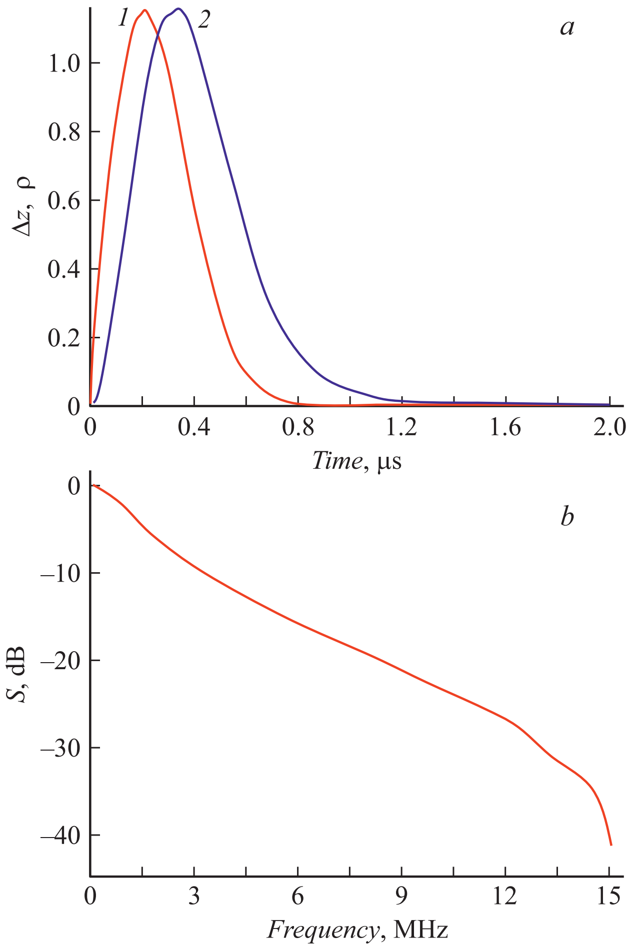

Figure 2. *a* — volume power density of heat release ρ (*1*) and offset of the active membrane center Δz (*2*) as functions of time for the active membrane thickness of 0.021 mm, its radius equal to 0.3 mm for the case of maximum released power equal to 10 mW. *b* — frequency response of photoacoustic generator membrane S calculated on the basis of simulation results using formula (1) (membrane thickness is 0.021 mm, membrane radius is 0.3 mm, maximum released power is 10 mW).

the dependence of membrane center offset on time is determined (required for the frequency response calculation by formula (1), an example is shown in Fig. 2, *b*), and its maximum value (offset amplitude) is determined as well. Thus, for each set of active membrane geometric dimensions one value of the membrane center offset amplitude and N samples of the frequency response are calculated, while the 6 dB bandwidth is used.

Fig. 3 shows three-dimensional dependencies of the membrane center offset amplitude $\Delta z(r, h)$ and the 6 dB bandwidth remove $\Delta f(r, h)$ on radius and thickness of the membrane represented as level lines. It can be seen, that with increase in membrane thickness the 6 dB bandwidth decreases. However, with increase in heat release power for small radii of membrane „stretching“ of constant remove bandwidth level lines along the axis of membrane thickness is observed, i. e. at small membrane radii the dependence

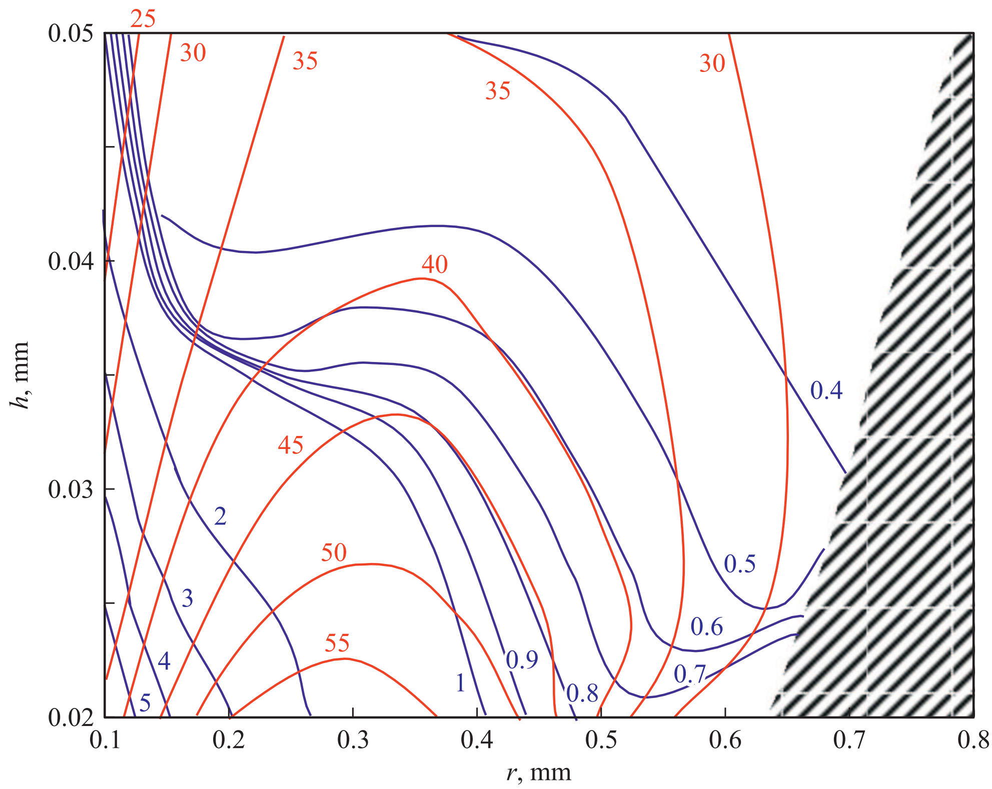

Figure 3. Dependencies of 6 dB bandwidth [MHz] (blue lines) and membrane center offset amplitude [μm] (red lines) on radius and thickness of photoacoustic generator membrane shown as level lines for the heat release power of 40 mW. Shaded area shows the zone of non-linear oscillations. Colored version of the figure is presented in electronic version of the article.

of remove bandwidth on its thickness becomes weaker with increase in heat release power. This is due to the linearization of the solution for the generally non-linear problem of nonsteady heat release. With increase in membrane radius the amplitude of membrane center offset first increases, then it decreases: the maximum offset amplitude is achieved at membrane radii in the range of 0.2 through 0.4 mm at a membrane thickness of ~ 0.02 mm, and with increase in thickness this area is narrowed. At the heat release power of 40 mW, remove optimum values of the operating remove bandwidth and the amplitude of membrane center offset can not be achieved simultaneously.

The highest bandwidth of the structure is achieved at membrane radii of 0.1–0.15 mm, while the biggest offset is achieved at radii of 0.2 through 0.4 mm and a thickness near 0.02 mm. The frequency remove greater than 5 MHz is achieved in the studied case at the offset amplitude over 35–40 μm. For a heat release power of 40 mW, remove maximum increase in temperature does not exceed 100 K, which ensures long-term operation due to properties of the material used [9,15]. In the area on non-linear oscillations, mechanical return forces arise in the membrane that make it bowing in the direction opposite to the initial deformation.

Thus, depending on geometric dimensions of the photoacoustic generator active membrane, there are ranges of parameters for both the mode of generation of fundamental frequency forced oscillations and the mode of non-linear generation of a set of harmonics of the exciting modulated optical signal, which makes considerably more difficult the use of such membranes in real systems of photoacoustics remove. For membranes made of polydimethylsiloxane, with a heat release power of 40 mW a fundamental frequency bandwidth greater than 5 MHz is achieved at membrane radii of 0.1–0.15 mm, while the offset amplitude exceeds 35–40 μm and no structure overheating is observed, which ensures its long-term functioning.

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Conflict of interest

The authors declare that they have no conflict of interest.

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