Determination of the optical characteristics of turbid media by the laser optoacoustic method

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Abstract. A method, based on the optoacoustic effect for determination of the spatial distribution of the light intensity in turbid media and of the optical characteristics of such media was proposed (and implemented experimentally). A temporal profile of the pressure of a thermo-optically excited acoustic pulse was found to be governed by the absorption coefficient and by the spatial distribution of the light intensity in the investigated medium. The absorption coefficient and the reduced light-scattering coefficient of model turbid water-like media were measured by the optoacoustic method. The results of a direct determination of the spatial light-intensity distribution agreed with a theoretical calculation made in the diffusion approximation.

1. Introduction

Study of the distribution of the optical radiation in light-scattering media, and particularly of the distribution of absorbing and scattering inhomogeneities, is a fundamental scientific problem [1]. The recent interest in this problem is largely associated with the development of the optics of biological media and tissues (see, for example, the review by Tuchin [2]). The methods for investigation of the optical characteristics of turbid media, based on detection of the optical field scattered by a medium, are being widely discussed [3–7]. The separation of the scattering and absorption contributions to the attenuation of the light intensity is most difficult if one of the processes is much more effective than the other. This does in fact occur in the case of biological tissues: their light-scattering coefficient is 10–100 times greater than the absorption coefficient (see, for example, Cheong et al. [8]) and separate measurement of these quantities by the methods mentioned above meets with considerable difficulties.

In order to overcome these difficulties, an optoacoustic method (known also as the photoacoustic method) is proposed in the present study. It is based on the thermo-optical excitation of ultrasonic waves in a medium when pulsed laser radiation is absorbed in it [9]. An advantage of the optoacoustic method is the proportionality of the amplitude of the excited optoacoustic signal solely to the light-absorption coefficient, whereas in the case of an absorption-free turbid medium there is no optoacoustic signal.

When a laser pulse of duration much less than the transit time of an acoustic wave across the heat-release region is absorbed in a medium, the pressure profile of the optoacoustic signal repeats the spatial distribution of the heat sources in the medium [9]. In the case of homogeneously absorbing and turbid media, this distribution coincides with the spatial distribution of the light intensity in the medium, considered in the plane-optical-wave approximation. The distribution depends on the absorption and scattering coefficients, and also on the ratio of the refractive indices of the absorbing medium and of a transparent medium through which irradiation is carried out (see, for example, Refs [10] and [11]). By fitting this relationship to the pressure profile of the optoacoustic signal in the investigated turbid medium, it is possible to obtain the absorption and scattering coefficients. Thus, the proposed pulsed optoacoustic method permits direct determination of the optical characteristics of turbid media.

2. Theoretical calculation of the spatial distribution of the light intensity under multiple scattering conditions

We shall consider a semi-infinite medium with the absorption and scattering coefficients $\mu_a$ and $\mu_s$, respectively, occupying the half-space $z > 0$. Let us suppose that scattering predominates over absorption: $\mu_a \ll \mu_s = (1 - g)\mu_s$ (where $g$ is the reduced scattering coefficient; $g = \langle \cos \theta \rangle$ is the average cosine of the single-scattering angle $\theta$, i.e. that radiation undergoes multiple scattering in the medium [12]). When an optical pulse with a plane wavefront [and with a time dependence of the intensity $I_0 e^{i\omega t}$] and a characteristic duration of a laser pulse $t_\text{p}$ is incident on such a medium, the intensity of the radiation within the medium may be represented as the sum of the intensities of the attenuated primary beam of photons which have not yet been scattered, $I_0(z, t)$, and the diffuse scattered-light field $\Phi(z, t)$. The first of these components decreases rapidly with the increase in $z$ [12],

$$I_0(z, t) = I_0 e^{i\omega t} \exp[-(\mu_a + \mu_s)z],$$  

whereas the second may be found by solving the diffusion equation [12, 13]

$$\frac{\partial \Phi(z, t)}{\partial t} - D V^2 \Phi(z, t) + c \mu_s \Phi(z, t) = c S(z, t),$$  

where $c$ is the velocity of light in the medium; $D = c/(3\mu_s')$ is the diffusion coefficient of light [14]; $S(z, t)$ is the distribution of radiation sources in the medium. Eqn (2) is obtained from the familiar radiative transfer equation considered in the
diffusion approximation [12] (subject to the conditions that \( \mu_\| \ll \mu_\perp \) and that the distribution of the sources is isotropic). This equation describes quite well the function \( \Phi(z, t) \) far from the boundary of the turbid medium (for \( z \gg |t^\ast| = 1/\mu_\| \)) and from radiation sources.

If the photon lifetime in the medium \( (\mu_\| c)^{-1} \) is much shorter than the duration of a laser pulse \( (\mu_\| c t_\perp \gg 1), \) the scattering of light can be regarded as quasi-steady-state. In this case, a steady-state diffusion equation is obtained from Eqn (2) [15]:

\[
(\nabla^2 - \mu_{\text{eff}}^2) \Phi(z, t) = -\frac{cS(z, t)}{D},
\]

where \( \mu_{\text{eff}}^2 = c\mu_\|/D = 3\mu_\| \mu_\perp \). The boundary condition for \( \Phi(z, t) \) on the surface of the medium and the distribution function \( S(z, t) \) of the sources can be expressed in the form

\[
\Phi(z = -z_0, t) = 0,
\]

\[
S(z, t) = I_0 f(t) \delta(z - z_1),
\]

where \( z = -z_0 \) is the 'extrapolated boundary' [16]; \( \delta(z) \) is the Dirac delta function; \( z_1 \approx |t^\ast| \) is the depth at which the collimated radiation incident on the medium is transformed into diffuse radiation; \( z_0 = D t^\ast; \) \( D \) is a constant which depends on the ratio of the refractive indices of the transparent \( (n_1)\) and turbid \( (n_2)\) media. The exact solution of the Milne problem concerning reflection of a plane optical wave from a semi-infinite randomly inhomogeneous medium (for \( n_1 = n_2 \)) yields \( D = 0.7104 \) [15]. When \( n_1 \neq n_2 \), the calculation of \( D \) must take into account reflection of part of the radiation at the boundary of the turbid medium. This leads to the following result [17, 18]:

\[
D = \frac{2}{3} \left( 1 + \frac{R_{\text{eff}}}{1 - R_{\text{eff}}} \right),
\]

where

\[
R_{\text{eff}} = \frac{R_t + R_1}{2 - R_t + R_1}
\]

is the effective reflection coefficient of the diffuse radiation from the interface;

\[
R_t = 2 \int_0^{\pi/2} R_P(\theta) \sin \theta \cos \theta d\theta;
\]

\[
R_1 = 3 \int_0^{\pi/2} R_P(\theta) \sin \theta \cos^2 \theta d\theta;
\]

\[
R_P(\theta) = 1 - \left( \frac{1}{2} \left[ \frac{n_2 \cos \theta_2 - n_1 \cos \theta_1}{n_2 \cos \theta_2 + n_1 \cos \theta_1} \right]^2 + \frac{1}{2} \left[ \frac{n_2 \cos \theta - n_1 \cos \theta_2}{n_2 \cos \theta + n_1 \cos \theta_2} \right]^2 \right) ;
\]

\[
0 \leq \theta < \theta_t ;
\]

\[
\theta_t = \arcsin(n_1/n_2) \quad \text{is the angle of total internal reflection};
\]

\[
\theta_2 = \arcsin(n_1/n_2) \sin \theta.
\]

The solution of Eqn (3) with the boundary condition (4), taking into account expression (5) for \( z \gg z_1 \approx |t^\ast| \), is of the form

\[
\Phi(z, t) = \frac{c I_0 f(t)}{2 \mu_{\text{eff}} D} \exp[-\mu_{\text{eff}}(z - z_1)] 
\]

\[
\times \left( 1 - \exp[-2\mu_{\text{eff}}(z_0 + z_1)] \right) \approx I_0 f(t) \frac{3}{2 \mu_{\text{eff}}^2 I^2} 
\]

\[
\times \left( \exp(\mu_{\text{eff}} I^\ast) - \exp(-\mu_{\text{eff}} I^\ast(2A + 1)) \right) \exp(-\mu_{\text{eff}} z) .
\]

Thus, the light intensity within the turbid medium at distances \( z \gg |t^\ast| \) is

\[
I(z, t) = I(z)f(t) = I_0 f(t) \exp[-(\mu_\| + \mu_\perp)z] 
\]

\[
+ \Phi(z, t) = I_0 f(t) h(z),
\]

where the function

\[
h(z) = \frac{I(z)}{I_0} = \exp[-(\mu_\| + \mu_\perp)z] + \frac{3}{2 \mu_{\text{eff}}^2 I^2} 
\]

\[
\times \left( \exp(\mu_{\text{eff}} I^\ast) - \exp(-\mu_{\text{eff}} I^\ast(2A + 1)) \right) \exp(-\mu_{\text{eff}} z) .
\]

(12)

describes the spatial light-intensity distribution in the diffusion approximation. At distances \( z \gg |t^\ast| \) this function is determined solely by the diffuse component of the scattered optical field [the second term in expression (12)], because in the approximation \( \mu_\| \ll \mu_\perp \) the extinction coefficient is \( \mu_{\text{eff}} \ll \mu_\perp \). The expression \( \mu_{\text{eff}} = [3\mu_\| (\mu_\| + \mu_\perp)]^{1/3} \) employed traditionally [19, 20] for \( \mu_\| \ll \mu_\perp \) is outside the limits of accuracy of the model and, in the diffusion approximation, this expression is identical with that introduced above [see Eqn (3)].

In general, the light intensity in a scattering medium is represented in the form \( I(z, t) = I_0 f(t) H(z) \), but in the region \( 0 \leq z \leq |t^\ast| \) the spatial distribution of the light intensity in the medium \( H(z) \) cannot be described by an analytical function [19, 20]. Numerical modelling by the Monte Carlo method shows that \( H(z) \) has a local minimum at the boundary \( z = 0 \) of a turbid medium, and at a distance \( z \approx |t^\ast|/2 \) a light-intensity maximum is observed. On the other hand, when \( z \gg (1.5 - 2)|t^\ast| \) the intensity distribution \( H(z) \) is identical with the distribution \( h(z) \) [12], so that at such distances the diffusion approximation can be used to calculate the spatial distribution of the light intensity in a turbid medium.

3. Theoretical model of the pulsed optoacoustic effect in a turbid medium

The solution of the problem of pulsed laser excitation of sound will be divided into three stages: calculation of the heat-release density in a turbid medium, calculation of the thermal field in a medium generated by the heat sources found in the first stage, and the calculation in the medium of the acoustic field emitted by the thermal fields calculated above. Since each of these problems has no analytical solution in general, an analysis of the thermo-optical excitation of sound in a turbid medium is possible only subject to additional simplifying postulates.

Suppose that the medium is turbid \( (\mu_\| \ll \mu_\perp) \), and that its thickness \( L \) and the characteristic radius \( a_0 \) of the laser beam used to excite the sound are much greater than the depth of penetration of light into the medium \( z_1 \approx \mu_{\text{eff}}^{-1} \). It is then permissible to use the semi-infinite-medium approximation and to assume that the laser beam is collimated. This makes it possible to employ the results from Section 2 to solve the optical (first) part of the problem of the laser excitation of
sound and to confine ourselves to one-dimensional acoustic and thermal problems [9].

Since the investigated medium scatters light strongly, the size $r_0$ of the inhomogeneities is of the order of magnitude of the wavelength of light $\lambda_\text{opt}$: $r_0 \sim \lambda_\text{opt}$. On the other hand, in a wide range of ultrasonic frequencies up to hundreds of megahertz we can assume that $\lambda_\text{opt} \ll \lambda_\text{ac}$ ($\lambda_\text{th}$ and $\lambda_\text{ac}$ are the thermal and acoustic wavelengths), so that the investigated medium can be regarded as acoustically and thermally homogeneous, and to describe it by certain ‘effective’ parameters: the specific heat $c_\rho$, the velocity of sound $c_0$, the coefficient of thermal expansion $\beta$, and the thermal diffusivity $\chi$. If the relaxation time of the thermal field in the heat-release region $\tau_\text{th} \approx 1/(\mu_\text{eff}^2)\chi$ is much longer than the laser pulse duration $\tau_L$, then the diffusion of heat during laser heating of the medium may be neglected.

When a short laser pulse ($\mu_\text{eff}c_0\tau_L \ll 1$) is absorbed in the medium, the intensity of the radiation in the latter is $I_0\delta(\delta(t)H(z)) = I_0\delta(\delta(t)H(z)) = E_0\delta(\delta(t)H(z))$, where $E_0$ is the laser-energy density on the surface of the medium (at $z = 0$). Subject to the assumptions indicated above, in this case the time dependence of the pressure in a travelling acoustic wave emitted into the absorbing medium [9, 21, 22] has the form

$$p(t) = \chi(1 - \frac{z}{c_0}) = \frac{\beta c_0^2}{2c_p}$$

\[ \times \mu_\text{eff} E_0 \left\{ \begin{array}{ll} H(-c_0 t), & \tau < 0 \\ (1 - N)/(1 + N)H(c_0 t), & \tau > 0 \end{array} \right. . \quad (13) \]

Here, $N$ is the ratio of the acoustic impedances of the absorbing and transparent media (for an acoustically rigid boundary of the absorbing medium we have $N = 1$, and for a free boundary we find that $N = 1$); $(1 - N)/(1 + N) = R_{ac}$ is the coefficient of reflection of the ultrasonic wave from the interface. Thus, the optoacoustic signal described by expression (13) represents a compression wave and a rarefaction (for $N > 1$) or compression (for $N < 1$) wave following it. For small but finite values of $\mu_\text{eff}c_0\tau_L \ll 1$, the transition zone between the phases lasts for an interval of the order of $\tau_L$. The total duration of the optoacoustic signal is determined by the sound transit time across the heat-evolution region and amounts to $(4 - 6)/(\mu_\text{eff}c_0)^{-1}$.

It is essential to note that expression (13) was obtained ignoring the diffraction of the optoacoustic signal during its propagation in the investigated medium. The quantity $p_0(t)$ may be found from the experimentally recorded time profile of the optoacoustic signal $p_0(t)$ transmitted through the investigated medium of thickness $L$ [9, 21]:

$$p(t) = p_0(t) + \omega_d \int_0^t p_0(\chi) d\chi,$$  

where $\omega_d = 2c_0L/a_0^3$ is the frequency of the wave for which the diffraction length is $L$; $a_0$ is the acoustic-beam radius on the surface of the medium, which is identical with the laser-beam radius.

As can be seen from expression (13), the leading edge of the optoacoustic signal $p(t < 0)$ repeats the spatial distribution of the light intensity in the medium. Moreover, the time scale of the variation of $p$ and the spatial scale of the variation of $H$ are related via the velocity of sound in the medium: $z = -c_0t$. When the optoacoustic signals are recorded directly (in an absorbing medium) [21, 22], the instant $\tau = 0$ corresponds to the arrival at an acoustic detector of a signal excited on the surface of the investigated medium. For a free surface of an absorbing medium, we have $p(t = 0) = 0$ (the signal is reflected by the surface in antiphase), whereas for a rigid boundary $p(t = 0)$ there is a local minimum [23] corresponding to a local minimum of the distribution $H(z)$ of the light intensity in the medium at $z = 0$. Determination of the instant $t = 0$ on the experimental pressure profile of an optoacoustic signal, corrected taking into account expression (14), makes it possible to convert the time dependence of the leading edge of the signal $p(t < 0)$ into the spatial relationship $p(z = -c_0t > 0)$. This relationship, normalised to $(\beta c_0^2/2c_p)\mu_\text{eff} E_0$, represents the distribution of the light intensity in the medium $H(z)$ [see expression (13)]. The optoacoustic method thus makes it possible to determine directly the spatial distribution of the light intensity in a turbid medium provided that the light-absorption coefficient, the velocity of sound, and the thermophysical parameters of the medium, as well as the laser radiation energy density on the surface of the medium are known.

At distances $z \gg (1.5 - 2)l^*$, we have $H(z) = h(z)$, so that [see expressions (12) and (13)]

$$p(z) = \frac{\beta c_0^2}{2c_p} \mu_\text{eff} E_0 \frac{3}{2\mu_\text{eff}^2} \left\{ \exp(\mu_\text{eff} l^*) - \exp[-\mu_\text{eff} l^*(2.4 + 1)] \right\} \times \exp(-\mu_\text{eff} z)$$

\[ = \frac{\beta c_0^2}{4c_p} \mu_\text{eff} E_0 \left\{ \exp(\mu_\text{eff} l^*) - \exp[-\mu_\text{eff} l^*(2.4 + 1)] \right\} \times \exp(-\mu_\text{eff} z) \]

\[ = \frac{\beta c_0^2}{4c_p} \mu_\text{eff} E_0 \delta(z). \quad (15) \]

For a turbid medium with unknown optical characteristics, it is possible to use the exponential dependence of the leading edge of the optoacoustic signal $p(t < 0) \sim \exp(\mu_\text{eff}z)$ to determine the extinction coefficient $\mu_\text{eff} = (3\mu_\text{th} l^*)^{1/2}$. The absolute pressure of the optoacoustic signal $H(z)$, normalised to $(\beta c_0^2/4c_p)\mu_\text{eff} E_0$ in the region where an exponential fall of the signal is observed, can be used to determine $l^* = 1/\mu_\text{e}$. Knowing $\mu_\text{eff}$ and $l^*$, it is possible to find $\mu_\text{th}$ and $\mu_\text{e}$.

The optical characteristics of a turbid medium, namely the absorption coefficient and the reduced scattering coefficient, may thus be calculated from the profile of the leading edge of the optoacoustic pressure signal recorded with a high temporal resolution.

4. Experimental setup and test samples

The optical characteristics of turbid media were determined by the optoacoustic pulse method on apparatus assembled to form a system for direct detection of optoacoustic signals (Fig. 1). The media were excited by the fundamental-harmonic radiation (wavelength 1.06 $\mu$m) of a pulsed Q-switched Nd : YAG laser $l$ (characteristic pulse duration $\tau_L = 10$ ns). The pulse energy could be varied by means of neutral light filters (not shown in Fig. 1) and amounted to 50 – 70 mJ. The bulk of the radiation was directed by a prism (2) through a glass diffuser (3) (in order to obtain a smooth intensity distribution in the beam) into a cell (4) with the investigated liquid turbid medium. The cell diameter was 6 cm and its height was $L = 2$ cm. The cell was in acoustic
contact with a broad-band piezoelectric detector (5) made from PVDF (polyvinylidene fluoride) film 110 μm thick. The cell was subjected to absolute calibration by the method of Andreev et al. [24] in the range 0.03–8 MHz; the low-frequency sensitivity of the detector was 13.5 ± 0.1 mV Pa⁻¹.

In order to ensure an acoustically rigid boundary of the investigated medium, the cell was covered by a quartz plate (6) (N ≈ 0.1). In the absence of this plate, the investigated medium—air interface was acoustically free (N ≈ 1). The transverse distribution of the laser radiation intensity on the surface of the investigated medium was close to Gaussian with a characteristic beam radius a₀ = 2.6 cm. Some of the laser radiation energy was reflected by a beam-splitting plate (7) to an FK-2 photocathode (8), in order to monitor the pulse energy and profile. The electric signal from the piezoelectric detector was recorded by a Tektronix TDS-220 oscilloscope (9) (analogue bandwidth 100 MHz, sampling rate 1 GHz). The system was synchronised by a multichannel pulse generator (10) with controllable delays.

The apparatus described above can be used to excite and detect acoustic pulses of 500 ns–10 μs duration and with a pressure amplitude from 2–3 Pa (the signal was averaged over 64 events). This makes it possible to measure the extinction coefficient μ_eff in the range 1.5–100 cm⁻¹ for an absorption coefficient μₐ > 0.05 cm⁻¹. Since the thickness L of the investigated medium and the laser-beam radius a₀ satisfy the inequalities L, a₀ > μ_eff and μ_effσ₀τ₁ ≪ 1 for such values of μ_eff, the results in Sections 2 and 3 may be used in an analysis of the experimental profiles of the optoacoustic signals.

Aqueous suspension of spherical polystyrene particles (Bang Laboratories Inc., USA, particle radius r₀ = 0.38 μm, volume concentration nV = 0.75%) and a suspension of titanium oxide (TiO₂) particles in water (average particle diameter r₀ < 1 μm, nV = 0.2 – 1.7%) were the investigated model turbid media.

The reduced light-scattering coefficient μ'_s = 16.2 cm⁻¹ and the anisotropy factor g = 0.782 were calculated for the suspension of polystyrene particles in accordance with the Mie theory of light scattering by a spherical particle [25] (the known values of r₀ and nV and the refractive index of polystyrene n₀ = 1.56 at a wavelength of 1.06 μm were used). The absorption coefficient of the suspension was assumed to be virtually identical with that of water (μₐ = 0.16 cm⁻¹ at the wavelength of 1.06 μm [26]), because the absorption of light in polystyrene at this wavelength did not exceed 0.05 cm⁻¹ and the particle concentration was low. Evidently, μₐ ≪ μ'_s, so that it is possible to employ the results of Section 2 to analyse the light-intensity distribution in the suspension.

Since the volume concentration of the particles was low, the refractive index and the thermophysical parameters of the investigated media were assumed equal to their parameters for water (n₂ = 1.33, β₁ = 1.82 K⁻¹, cₚ₁ = 4.18 J g⁻¹ K⁻¹, χ₁ = 1.43 × 10⁻³ cm² s⁻¹ [26]). The ultrasound absorption coefficient in water in the investigated frequency range did not exceed 2.5 × 10⁻² cm⁻¹ and, therefore, its influence on the optoacoustic signal profile during propagation in a medium of thickness L = 2 cm was disregarded. The measured velocity of sound in the investigated media was c₀ = (1.49 ± 0.01) × 10⁵ cm s⁻¹. The relaxation time of the thermal field in the heat-release region in the range of light-extinction coefficients considered is tᵣ > 0.07 s, so that the diffusion of heat was insignificant within the limits of the laser pulse duration and the results of Section 3 could be used to analyse the optoacoustic effect in the investigated media.

### 5. Experimental results and discussion

The possibility of using the optoacoustic method in the investigation of the spatial distribution of the light intensity in turbid media and in determination of the optical characteristic was tested for an aqueous suspension of spherical polystyrene particles. Fig. 2 illustrates the time profiles of the optoacoustic signal excited in the suspension with a free boundary. The duration Δt of the transition from the compression to the rarefaction phase exceeded the laser pulse duration because the surface of the investigated medium with a free boundary was not planar and the pressure profile of the optoacoustic signal therefore repeated the spatial distribution of the light intensity in the suspension only at distances z > c₀Δt/2 ≈ 0.03 cm.

The extinction coefficient of the suspension μ_eff = 2.80 ± 0.03 cm⁻¹ was found from the time dependence of the leading edge of the optoacoustic signal p(τ < 0) ~ exp(μ_effc₀τ) (Fig. 2, exponential approximation). The relative

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**Figure 1.** Schematic diagram of the experimental setup used to determine the optical characteristics of turbid media: (1) pulsed Q-switched Nd·YAG laser; (2) rotatable prism; (3) glass light diffuser; (4) cell with the investigated medium; (5) acoustic detector; (6) quartz plate; (7) beam-splitting plate; (8) photocathode; (9) digital oscilloscope; (10) multichannel pulse generator.

**Figure 2.** Time profile of the optoacoustic pressure signal from an aqueous suspension of spherical polystyrene particles excited in the presence of a free boundary: (1) detected signal; (2) signal after compensation for the diffraction-induced distortions; the continuous curve is the exponential approximation.
error in the measurement of $\mu_{\text{eff}}$ was determined by the signal quantisation noise $p(t)$ and by the error in the measurement of the velocity of sound; it amounted to about 1% (when the signal is averaged). The reduced scattering coefficient $\mu_s' = \mu_{\text{eff}}/\rho_{\mu_s} = 16.3 \pm 0.3 \text{ cm}^{-1}$ was determined from the known absorption coefficient $\mu_a = 0.16 \text{ cm}^{-1}$ and the measured value of $\mu_{\text{eff}}$. Within the limits of the 2% experimental error, it agreed with the value calculated by the Mie theory (see Section 4). The spatial distribution of the light intensity $I(z)$ in the suspension was calculated from formula (12) and the known values of $\mu_a$ and $\mu_s'$ for the suspension–air interface, $\Delta = 1.66$; see expressions (6)–(9). The results of the calculation are presented in Fig. 3. Evidently, for $z > l^* = 1/\mu_s' \approx 0.06 \text{ cm}$ this distribution practically coincides with the profile of the leading edge of the optoacoustic pressure signal $p(z)$ normalised to $(\beta c_0/2c_p)\mu_a E_0$ (the energy density of the incident radiation was $E_0 = 0.95 \text{ mJ cm}^{-2}$). The error in determination of $p(z)$, and hence of the spatial distribution of the light intensity, originates mainly from the error in determination of the piezoelectric detector sensitivity and does not exceed 1% [the instability of the laser-radiation energy is approximately 3% and hardly affects the precision of measurement of $p(z)$ when the signal is averaged].

The results of this experiment confirmed the feasibility of using the optoacoustic method in determination of the spatial distribution of the light intensity and of the optical characteristics of turbid media from the time profile of the optoacoustic pressure signal.

Suspensions of TiO$_2$ particles in water with particle concentrations $n_V = 0.2\% - 1.7\%$ were used as the turbid media with unknown optical characteristics. Fig. 4a illustrates the time profile of the optoacoustic pressure signal excited in a suspension with a 0.3% concentration and a rigid boundary (after compensation for the diffraction-induced distortions). The local minimum at $\tau = 0$ corresponds to the arrival of the optoacoustic signal from the $z = 0$ surface of the investigated medium and $p(\tau > 0)$ is the signal reflected from a quartz plate ($R_{\text{ac}} = 0.81$). The light-extinction coefficient $\mu_{\text{eff}} = 4.09 \pm 0.04 \text{ cm}^{-1}$ was determined by fitting an exponential function to the $p(\tau < 0)$ front. Fig. 4b presents the leading-edge profile of a normalised optoacoustic signal $\zeta(z) = p(z)/(\beta c_0/2c_p)\mu_{\text{eff}} E_0$ ($E_0 = 1.57 \text{ mJ cm}^{-2}$). The value $l^* = (3.15 \pm 0.09) \times 10^{-2} \text{ cm}$ was deduced from the function $\zeta(z)$ in the region where an exponential decrease was observed [see expression (15)] for the suspension–quartz interface, $\Delta = 0.689$. Thus the reduced scattering coefficient $\mu_s' = 1/l^* = 31.7 \pm 0.87 \text{ cm}^{-1}$ and the absorption coefficient $\mu_a = \mu_{\text{eff}}/\mu_{\text{eff}}/l^* = (1.76 \pm 0.06) \times 10^{-1} \text{ cm}^{-1}$ were calculated for the given suspension of TiO$_2$ particles in water. Since $\mu_a \ll \mu_s'$, the use of the results in Sections 2 and 3 in calculation of the optical characteristics of the suspension is legitimate. The error of the determination of $\mu_s'$ and $\mu_a$ depends on the error in the measurement of the extinction coefficient $\mu_{\text{eff}}$ and of the optoacoustic-signal pressure $p(z)$. The optoacoustic method makes it thus possible to determine the optical characteristics of a turbid medium with a relative error of 2.5%–3%.

The dependence of the extinction coefficient $\mu_{\text{eff}}$ on the volume concentration of particles $n_V$ was determined for a

![Figure 3](image-url)  
**Figure 3.** Spatial distribution of the light intensity in an aqueous suspension of spherical polystyrene particles: calculated from formula (12) for $\mu_{\text{eff}} = 2.8 \text{ cm}^{-1}$ and $l^* = 6.13 \times 10^{-2} \text{ cm}$ (continuous curve) and the leading edge of the optoacoustic pressure signal, normalised to $(\beta c_0/2c_p)\mu_{\text{eff}} E_0$ (dots).

![Figure 4](image-url)  
**Figure 4.** Time profile of the optoacoustic pressure signal $p$ of a suspension of TiO$_2$ particles in water with a rigid boundary (circles—experiment, continuous curve—exponential approximation) (a) and the leading edge of the optoacoustic pressure signal $p'$ normalised to $(\beta c_0/2c_p)\mu_{\text{eff}} E_0$ for $\mu_{\text{eff}} = 4.09 \text{ cm}^{-1}$ and $l^* = 3.15 \times 10^{-2} \text{ cm}$ (circles—experiment, continuous curve—fit of formula (15) to the function $\zeta(z)$) (b).

![Figure 5](image-url)  
**Figure 5.** Experimental dependence of the square of the light-extinction coefficient of a suspension of TiO$_2$ particles in water on the volume concentration of the particles (circles) and its linear fit (continuous line).
suspension of TiO$_2$ particles in water (particle concentration $n_V = 0.2\% - 1.7\%$) by the optoacoustic method. Fig. 5 gives the dependence $\mu_{\text{eff}}(n_v)$, which shows that $\mu_{\text{eff}} \propto n_v^{1/2}$ in the range $\mu_s < \mu_i$. This means that the reduced scattering coefficient is $\mu_s' \propto n_v$ and that the Born approximation may be used to calculate $\mu_i$ for a scattering-particle concentration $n_v < 2\%$.

6. Conclusions

The proposed and experimentally implemented optoacoustic laser method makes it possible to investigate the spatial distribution of the light intensity and the optical characteristics of turbid media. The apparatus which we constructed can be used to determine the light-extinction coefficient in the range 1.5 – 100 cm$^{-1}$ when the absorption coefficient is more than 0.05 cm$^{-1}$. The results of a direct determination of the spatial light-intensity distribution from the time profile of the optoacoustic pressure signal agree with the results of our theoretical calculation made in the diffusion approximation. The optical characteristics (the absorption coefficient and the reduced light-scattering coefficient) were measured for model water-like turbid media. For a medium with spherical scattering particles of known radius and with a known volume concentration the reduced scattering coefficient agrees with the coefficient calculated from the Mie light-scattering theory within the limits of the 2% error. It was demonstrated experimentally that, for a volume concentration of particles less than 2%, the reduced scattering coefficient is proportional to the concentration of the scattering particles.

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References