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Determination of optical characteristics of tissues

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Radiative transfer equation

$$\frac{1}{v}\frac{\partial}{\partial t}\Phi\left(\vec{r},\vec{\Omega},t\right)+\vec{\Omega}grad\left(\Phi\left(\vec{r},\vec{\Omega},t\right)\right)+$$

$$+\mu\left(\vec{r}\right)\Phi\left(\vec{r},\vec{\Omega},t\right)-\oiint_{4\pi}\Phi\left(\vec{r},\vec{\Omega}',t\right)\mu_s\left(\vec{r},\vec{\Omega}'\to\vec{\Omega}\right)d\Omega'=S\left(\vec{r},\vec{\Omega},t\right)$$

$S(\vec{r},\vec{\Omega},t)$ - the density of photon sources $\vec{r}$, at the point and at the instant t,
$\vec{\Omega}$ is the direction of motion of photons

$\Phi(\vec{r},\vec{\Omega},t)$ - the density of the photon flux at the point $\vec{r}$, and at the instant *t*, $\vec{\Omega}$

$\mu_s(\vec{r})=\oiint_{4\pi}\mu_s(\vec{r},\vec{\Omega}'\to\vec{\Omega})d\Omega'=\oiint_{4\pi}\mu_s(\vec{r},\vec{\Omega}'\to\vec{\Omega})d\Omega$ - the coefficient of radiation scattering

v - the modulus of the velocity with which the radiation propagates in the medium.

Experiment on determining optical characteristics of an HSM layer

One can determine the optical characteristics of a homogeneous scattering HSM layer from the results of measurements in the following way. The ray of the laser pulse radiation is directed perpendicular to the studied layer, and the temporal distribution *T(l,t)* of the pulse passed through the scattering layer at the ray axis is detected.

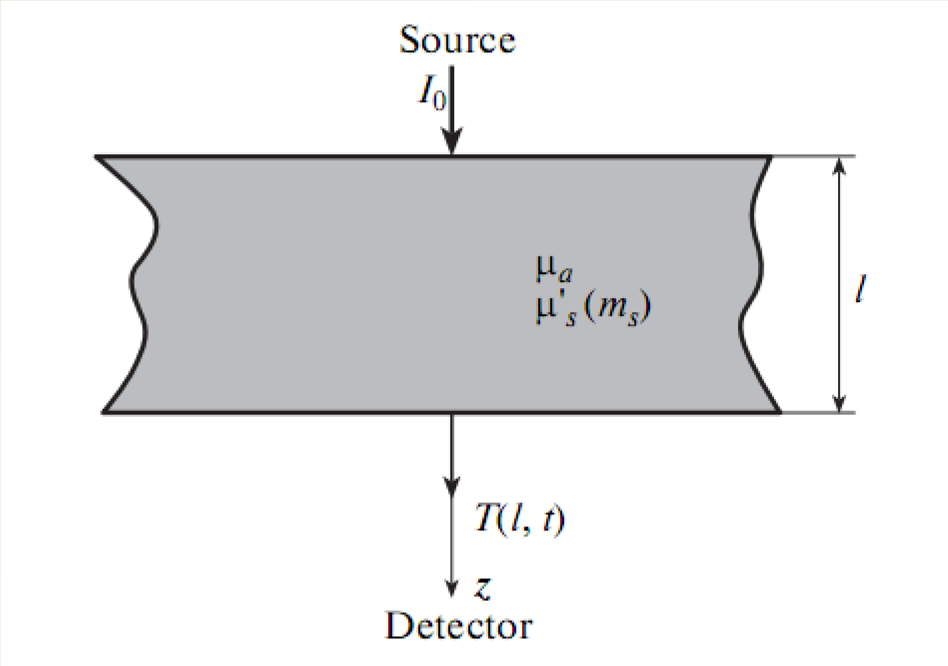

Fig. 1. Scheme of experiment on determining optical characteristics of an HSM layer.

Diffusion model

$$T(z,t)=\frac{1}{2}(4\pi Dv)^{-3/2}t^{-5/2}U_0\exp(-\mu_a vt)\times \times\left|(z-z_0)\exp\left(-\frac{(z-z_0)^2}{4Dvt}\right)-(z+z_0)\exp\left(-\frac{(z-z_0)^2}{4Dvt}\right)\right|, \quad (1)$$

$$T(z,t)=\frac{1}{4t}U_0\eta(t)(4\pi Dvt)^{-3/2}e^{-\mu_a vt}\times \times\left|(vt-z)\left(e^{-\frac{(z-z_0)^2}{4Dvt}}-e^{-\frac{(z+z_0)^2}{4Dvt}}\right)+z_0\left(e^{-\frac{(z-z_0)^2}{4Dvt}}+e^{-\frac{(z+z_0)^2}{4Dvt}}\right)\right|. \quad (2)$$

$$T(z,t)=\frac{3}{2}U_0(4\pi Dvt)^{-3/2}\exp(-\mu_a vt)\exp\left(-\frac{z^2}{4Dvt}\right)\frac{(z^2+zvt-2Dvt)}{2vt^2} \quad (3)$$

Nonstationary axial model

$$\mu_s\left(\vec{\Omega}' \to \vec{\Omega}\right) = m_s\,\delta_2\left(-\vec{\Omega}\vec{\Omega}'\right) \qquad (1)$$

$$T(z,t) = \frac{2\pi U_0 v \mu_s z}{\sqrt{(vt)^2 - z^2}}\,\eta(vt - z) I_1\left(\mu_s\sqrt{(vt)^2 - z^2}\right)\exp(-\mu v t), \qquad (2)$$

Temporal distributions of the laser pulse passed through HSM layer

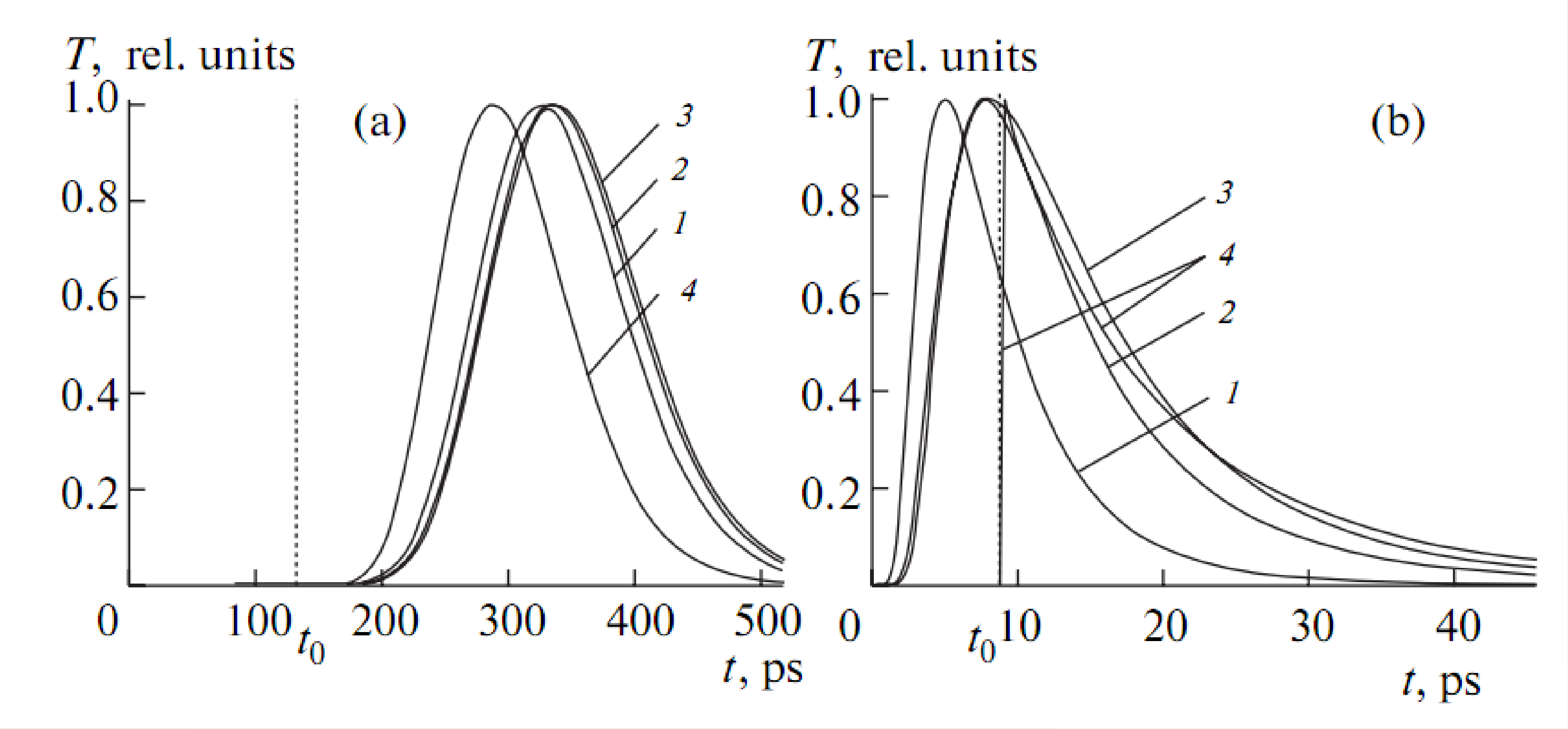

Fig. 2. Temporal distributions of the laser pulse passed through HSM layer with thickness (a) z = 30 mm and (b) z = 2 mm: (1)CDM; (2) RDM; (3) MDM; (4) NAM; $\mu_a = 0.2\ \text{mm}^{-1}$ and $m_s = m'_s = 1.8\ \text{mm}^{-1}$ (t_0 is the arrival time of the ballistic photons).

Applicability domain of models

Considering that the main part of the temporal distribution must be in the permissible domain $t > t_0$, one can define the applicability domain of the model in the plane of the HSM characteristics (($\mu_a l, \mu_s l$)).

As should be expected, the applicability domain for the MDM and RDM is, to some extent, wider than for the CDM.

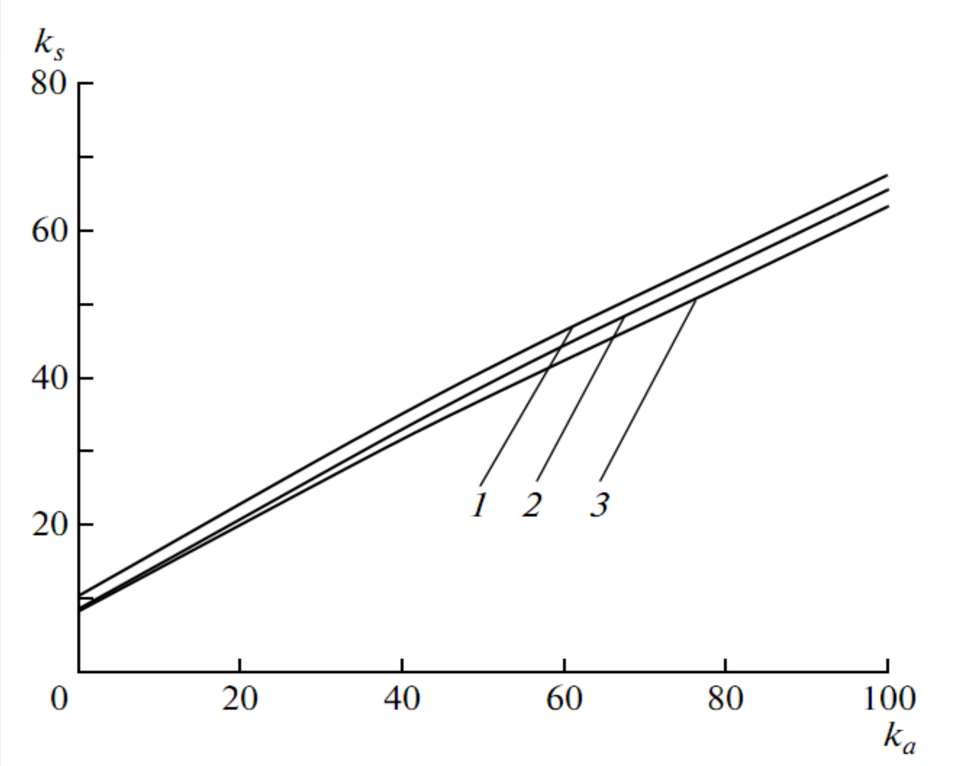

Fig. 3. Applicability domain of models (above the corresponding curve): (1) CDM, (2) MDM, and (3) RDM ($k_a = \mu_a l, k_s = \mu_s l$).

Optical characteristics of a homogeneous HSM

Model	Thickness l of an HSM layer, mm					
	$l = 30$		$l = 40$		$l = 50$	
	μ_a, mm^{-1}	μ_s' (m_s), mm^{-1}	μ_a, mm^{-1}	μ_s' (m_s), mm^{-1}	μ_a, mm^{-1}	μ_s' (m_s), mm^{-1}
CDM	0.0025	0.81	0.0016	0.77	0.0026	0.78
MDM	0.0069	0.69	0.0042	0.65	0.0043	0.68
RDM	0.0067	0.73	0.0041	0.69	0.0043	0.70
NAM	0.0095	0.85	0.0059	0.81	0.0056	0.87

Model	Thickness of the layer for determining HSM characteristics, mm					
	30		40		50	
	Layer thickness for forecasting, mm					
	40	50	30	50	30	40
CDM	0.045	0.051	0.038	0.070	0.029	0.025
MDM	0.069	0.123	0.093	0.013	0.102	0.051
RDM	0.063	0.110	0.088	0.013	0.091	0.047
NAM	0.112	0.199	0.134	0.049	0.171	0.081

Root-mean-square deviation of theoretical temporal distributions obtained by different models from experimental temporal distributions at different layer thickness

Temporal distributions of ultrashort laser pulse

Temporal distributions of ultrashort laser pulse passed through HSM layer with thickness of (c, e) 30, (a, f) 40, and (b, d) 50 mm: experimental (open symbols) and theoretical temporal distributions obtained for optical characteristics found for HSM layer with a thickness of (a, b) 30, (c, d) 40, and (e, f) 50 mm; 30 (a, b), 40 (c, d), 50 mm (e, f); (1) CDM; (2) RDM; (3)MDM; (4)NAM.

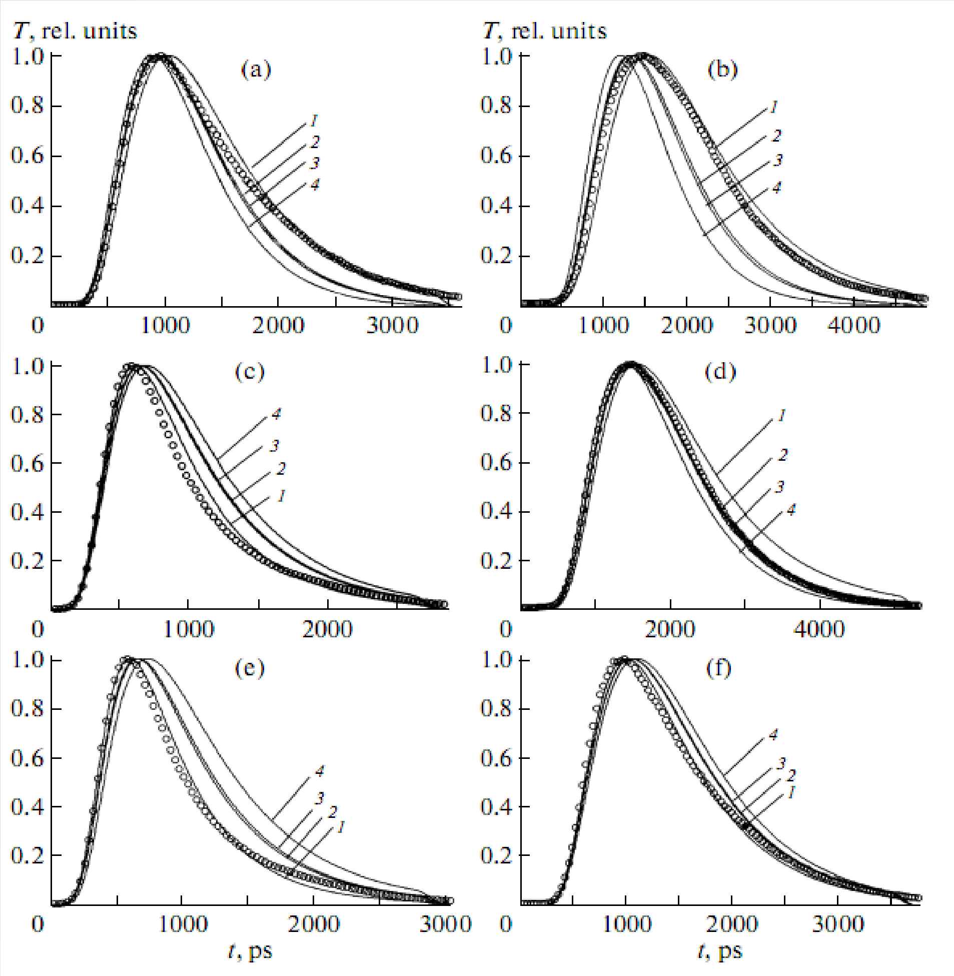

Fig. 4. Temporal distributions of ultrashort laser pulse

Conclusions

The performed study of the four models of the transmission of optical radiation through a homogeneous layer of a highly scattering medium demonstrated the following:

1. Among the diffusion models, the RDM can be used in the widest range of the absorption and scattering coefficients, and the CDM in their narrowest range.
2. The determination of HSM optical characteristics by experimental temporal distributions leads to different numerical values depending on the used model.
3. The comparison of the models by their forecasting properties does not permit one to give preference to any of the studied models.

Thus, the optical characteristics of scattering samples can be determined by any of the studied models. However, it is necessary to specify the used model and the conditions under which the initial experimental data (in particular, the value of the layer thickness of the studied sample) were obtained.