A thermal lens response of the two components liquid in a thin film cell

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Abstract. It was proposed a new thermal lens scheme with a thin layer of cell thickness which is significantly less than the size of the beam. As a result the exact analytical expression for the thermal lens response is achieved, taking into account the thermal lens in the windows of the cell.

1. Introduction
The thermal lens method is widely used in spectrometry and thermo-optical diagnostics of materials [1-3]. The application of this method in the two-component liquid has its own peculiarities, because in addition to normal thermal response associated with thermal expansion of environment here it may arise resulting from flows of concentration phenomenon of thermal diffusion (effect of Soret) [2-5].

This component concentration redistribution results a corresponding change in the refractive index (and absorption) of the liquid. We propose a thermal lens scheme with thin-layer cell in which the cell thickness is significantly less than the size of the beam.

2. A thermal lens response in the thin optical cell with two-component liquid
We consider the one-beam scheme of the thermal lens signal measurement (fig. 1). Let’s the absorption coefficient $\alpha$ is determined entirely by one component with mass concentration $C$ ($\alpha = \beta C$, where $\beta = (\partial \alpha / \partial \tau)_{\text{constant}}$) and liquid is located in a thin cell with thickness $d_0$.

We have for a Gaussian beam distribution in a plane perpendicular to the optical axis $z$:

$$I = I_0 \left[ 1 + \left( \frac{z}{\pi r_0^2} \right)^2 \right]^{-1} \exp\left( -r^2(z)/r_0^2(z) \right),$$

(1)

the radius of the beam $r(z) = r_0 \left[ 1 + \left( \frac{z}{\pi r_0^2} \right)^2 \right]^{0.5}$, $r$ – the distance from the axis of the beam, $\lambda$ - radiation wavelength, $r_0$ - the radius of the beam in the beam waist, $I_0$ - intensity of radiation on the axis in the plane in the beam waist, $I(r, z)$ - radiation intensity ($\alpha d_0 << 1$ ).

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We assume small thicknesses of liquid layer $d$ and cell window $L$ ($d, L \ll r_1$). In this case the radial heat flow is negligible and we get a one-dimensional thermal task:

$$\frac{c_m}{\rho_m} \frac{dT_m}{dt} = -\frac{\chi_m}{\rho_m} \frac{d^2 T_m}{dz^2} + \alpha I(r,z), \quad (2)$$

were $c_m, \rho_m$ - specific heat capacity and density environment, $T_m$ - liquid temperature, $\chi_m$ - heat conductivity coefficient.

The similarly thermal task is considered challenge for the temperature in the window of the cell $T_w$:

$$\frac{c_w}{\rho_w} \frac{dT_w}{dt} = -\frac{\chi_w}{\rho_w} \frac{d^2 T_w}{dz^2}, \quad (3)$$

where $c_w, \rho_w, \chi_w$ - thermo-physical window material parameters.

Boundary conditions on the borders are next:

$$\chi_w (dT_w / dz)_{z=L+d/2} = \gamma (T_w - T_0). \quad (4)$$

$$T_m(d/2) = T_w(d/2). \quad (5)$$

$$\chi_m (dT_m / dz)_{z=d/2} = \chi_w (dT_w / dz)_{z=d/2}. \quad (6)$$

where $\gamma, T_0$ - the convective heat transfer coefficient and ambient temperature accordingly, $T_j = T_w(L + d / 2)$.

In the stationary mode we have the following system solution for the distribution of temperature in the liquid $T_m^*$ and the cell window $T_w^*$:
\[ T_m^* = T_0 + T(d/2) + \alpha I(r) \chi_m^{-1} \left\{ \left( d/2 \right)^2 - z^2 \right\}, \quad (7) \]

\[ T_w^* = T_0 + T(d/2) + \alpha d I(r) \chi_w^{-1} \left\{ \left( d/2 \right) - z \right\}, \quad (8) \]

\[ T(d/2) = \alpha I(r) d \left( \gamma^{-1} - L \chi_w^{-1} \right). \quad (9) \]

Now let’s consider the effect of thermal diffusion. Since the diffusion processes are much orders of magnitude slower than heat transfer processes, we can assume that thermal diffusion of absorbing component occurs in stationary temperature field, which is determined by formulas (7-9), but with a concentration-dependent absorption coefficient.

Balanced system of equations for the concentration of absorbing particles \( C \) is follows:

\[ \frac{dC}{dt} = -\nabla J, \quad (10) \]

\[ J = -D_{21} C \nabla T - D_{22} \nabla C, \quad (11) \]

here: \( J \) – concentration flow, \( D_{22} \) – the diffusion coefficient of absorbing particles, \( D_{21} \) – thermal diffusion coefficient. For layer thicknesses \( d_0 << L \) we can neglect the temperature change along \( o \) the thickness of cell and take it equal \( T(r, z = 0) \). In the set mode (\( (dC/dt) = 0 \)) we have from (10-11) for the stationary concentration \( C \):

\[ -D_{21} C \nabla T - D_{22} \nabla C = 0 \quad (12) \]

The concentration change of absorbing components is small compared to primary one - \( C_i = C - C_0 \), where \( C_i << C_0 \). Then we get the equation for \( C_i \):

\[ -\Delta_{thd} C_0 \nabla I - \nabla C_i = 0, \quad (13) \]

here we denoted the next values:

\[ \Delta_{thd} = \alpha_0 d(L \chi_0^{-1} + \gamma^{-1} + d \chi_c^{-1}/2)D_{21}D_{22}^{-1}, \quad \alpha_0 = \beta C_0. \]

Then we get from (13):

\[ C_i = -C_0 \Delta_{thd} I_0. \quad (14) \]

We use the term for the lens transparency cell to calculate the thermal lens signal [1]:

\[ \Theta = 1 - \frac{2\left(z_i/l_0^2\right)\Phi_n(0)}{\left(1 + z_i^2/l_0^2\right)\left(1 + 3z_i^2/l_0^2\right)}, \quad (15) \]

where \( l_0 = \pi r_0^2 / \lambda \), \( \Phi_n(0) \) - nonlinear phase in optical cell on the beam axis. The latter value includes the nonlinear phases in the liquid and in the windows of the cell:

\[ \Delta \Phi_n''(0) = 2k \int_0^{d/2} \left( \frac{\partial n_m}{\partial T} \right) \Delta T_m''(z, r = 0) dz. \quad (16) \]
\[ \Delta \Phi^w_m(0) = 2k \int_{d/2}^{d/2+L} \left( \frac{\partial n}{\partial T} \right) \Delta T^w_m(z, r = 0) \, dz , \quad (17) \]

where \( \left( \frac{\partial n_m}{\partial T} \right) \) and \( \left( \frac{\partial n_w}{\partial T} \right) \) are constant coefficients for nonlinear medium and material of the window respectively, \( k = 2\pi/\lambda \) - wave vector of radiation.

Using (15-17), we get:

\[ \Delta \Phi^w_m(0) = \alpha_o k I_0 d^2 \left\{ \gamma - L X^{-1} + d X_m^{-1} / 6 \right\} \left( 1 - \Delta_{\text{m,d}} I_0 \right) , \quad (18) \]

\[ \Delta \Phi^w_m(0) = \alpha_o k I_0 dL \left\{ \gamma - L X^{-1} + X_m^{-1} (L + d) \right\} \left( \frac{\partial n_w}{\partial T} \right) \left( 1 - \Delta_{\text{m,d}} I_0 \right) . \quad (19) \]

Finally we have an expression for the stationary lens transparency value:

\[ \Theta(t = \infty) = 1 - \frac{2 \left( \gamma I_0 / L \right) \left[ \Delta \Phi^v_m(0) + \Delta \Phi^w_m(0) \right]}{\left( 1 + \gamma^2 / I_0^2 \right) \left( 1 + 3 \gamma^2 / I_0^2 \right) } . \quad (20) \]

The resulting expression allows to calculate the influence of thermal diffusion on the value of the stationary thermal lens response in the optical cells with two-component liquid.

3. Conclusions

Thus it is shown that thermal lens response in the two-component liquid contains additional contribution due to thermodiffusion concentration change of absorbing components. The magnitude of this contribution can be quite large and it have a different sign for different liquids, depending on the sign of the coefficient of thermal diffusion. Secondly, the amount of thermal lens response will influence and change layer transmission. Thus a self-induced absorption coefficient modulation must be taken into account in the thermal lens spectroscopy analyses of the multi-component liquids [1-3]. Received expressions can be used in the experimental determination of the heat and mass transfer coefficients in such multi-component materials [4-6].

4. References

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