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Analytical study of flat-topped beam characterization using the thermal lens method in sample liquids

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In the present work, the effect of a thermal lens generated by a pump beam on the propagation of a flat-topped probe beam is investigated. The analysis of results shows that the thermal lens affects the probe beam waist radius, the far-field divergence angle and the waist position; this last one can be virtual or real according to the sign of the refractive index thermal gradient. Numerical simulations are performed to indicate the influence of thermal lens on the physical parameters of the flat-topped probe beam by considering the sample as a solvent and numerical results are given for many solvents with different absorption coefficient.

1. Introduction

The thermal lens (TL) is one of the most sensitive technical spectroscopy based on the lasers because to their many interesting properties such as low beam divergence, high intensity [1], high spectral and spatial resolution, and its capacity to be focused on a diffraction-limited spot. The thermal lens effect, first discovered by Gordon et al. [2], results when the propagation of light in an absorbing medium, placed inside the cavity laser, caused an increasing of the sample temperature along the beam path. As a consequence, a spatial distribution of the refractive index is generated in the absorbing medium due to its dependence on the temperature which produced a thermal lens at the sample. However because of the thermal diffusion, the lens expands into a volume much larger than the interaction volume defined in the sample by the pump beam and phase shifts are induced in the wave-fronts of the probe beam. According to the material, the variation of the refractive index coefficient with temperature is generally positive for solids where the laser beam behaves like a defocusing beam [3–5] and negative for gases and liquids; in this case the laser beam comports as a focused beam [6,7]. Experimentally, thermal lens technique is early used single-beam configuration where the excitation light source is used also as the source of the probe beam. This last one has generally a lower power and it serves to probe the thermal lens. Later, the dual-beam experimental arrangement is introduced where the pump and probe beams have produced by two different laser sources with a more powerful pump beam. On the other hand, there are two types of theoretical treatments for thermal lens: the aberrant and the parabolic models. In the aberrant model, the thermal lens is considered as an optical path length change of the probe beam which results a phase shift on the probe beam wave front at the output plane of sample. In the parabolic model, the distribution of the temperature sample caused by the optical absorption of the excitation laser energy is parabolic and the thermal lens behaves an ideal thin lens.

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TL method is a precious technique to investigate the thermo-optical properties of solid or liquid material; this technique is most applied to liquids [8–11], this is because the refractive index depends on the density and on the sensitivity of the measurement related to the temperature coefficient of the refractive index.

The TL is a photo-thermal method which has been widely used to determinate the low absorption coefficients and to measure the absorption coefficient of materials with high sensitivity and versatility [12–16]. On the other hand, the thermal lens method has for objective to facility the application of theories for physical characterization of medium, chemical analysis and to study transparent materials. However, we note large applications of thermal lens technique such as material testing [17], heat diffusion researches [18], combustion studies [19], and plasma diagnostic [20].

Later, based on the fundamental Gaussian beam propagation, Hu and Whinnery [21,22] are proposed a model to calculate the effects of the thermal lens. They explain that the change in the beam center intensity and in the spot radius are influenced by the absorption coefficient of the sample and they assume that the profile of the refractive index is parabolic, so the thermal lens is considered as perfect thin lens without aberrations. After, such theory is expanded by Twarowski and Kliger [23] to thermal lens effect measurements of multiphoton absorption studies by using pulsed laser beam. In another processing, Sheldon et al. [24] have presented an aberrant model of thermal lens in the single-beam situation by developing the theory of Gordon et al. [2]. Shen et al. [25–27] are generalized the work of Sheldon et al. [23] by using a Fresnel diffraction model integrating the effects of the aberrations lens introduced by the deviations in the thermal profile from the parabolic distribution.

In the literature, the all works using thermal lens technique have taking the Gaussian profile as probe and pump beam. In this paper, our objective is to consider the profile of the probe beam as flat-topped profile. This beam firstly suggested by Gori in 1994 [28]. The theoretical models characterizing the flat-topped beam are the super-Gaussian beam (SGB) model [29,30]. In our research group, some studies have been foe illustraticused on the flat-topped beams (FTB) as the effects of the atmospheric turbulence on the propagation of Li's flat-topped optical beams [31]. A. Chafiq et al. have studied the flat-topped Mathieu-Gauss beam and its transformation by paraxial optical systems [32]. Ez-zariy et al. have been interested to the generalization of the transformation of flat-topped Mathieu-Gauss beams by paraxial optical systems [33].

The aim of this paper is to investigate the characterization of flat-topped beam by using the thermal lens method. The results of Gaussian probe beam given by M. Yero et al. [34] are deduced as a particular case from the present study. In our numerical simulations the sample is assumed as a solvent such as Ethanol, Benzene, Toluene and chloroform.

The remaining parts of this paper are organized as follows: Section 2 is reserved to the theoretical and physical thermal lens method. Section 3 is focused on the developpement of intensity distribution of flat-topped probe beam after propagation through a thermal lens. We treated the characterization of the flat-topped probe beam by deriving the beam radius, the waist position and the far-field divergence angle, in Section 4. Some numerical simulations are illustrated in Section 5. A simple conclusion is outlined in Section 6.

2. Theoretical thermal lens method

We consider the propagation of a short pulse pump laser beam with a Gaussian profile via a sample liquid. The absorption of energy from the pump beam generates a spatial distribution of the temperature in the sample $T(r, \varphi, t)$, which is can be described by the following expression [35]

$$T(r,\varphi,t) = \frac{T_0}{\gamma}\exp\left(-2\frac{r^2}{\gamma\omega_e^2}\right), \tag{1}$$

where

$$T_0 = \frac{2\alpha E_0}{\pi\rho C_p \omega_e^2}, \tag{1.1}$$

$$\gamma = 1 + \frac{2t}{t_c}, \tag{1.2}$$

$$t_c = \frac{\omega_e^2}{4D}. \tag{1.3}$$

In these equations, α, ρ, D and C_p are the absorption coefficient, the density, the thermal diffusivity and the specific heat at constant pressure of the sample, respectively. The other parameters, ω_e and E_0 are the waist and the amplitude of Gaussian beam respectively, t holds for a variable of time, and the change in the optical path length, ΔOPL, results most strongly from change in the material's temperature dependent index of refraction $\frac{dn_r}{dT}$ of the probe beam due to the thermal lens. The variation of optical path length is giving by the formula

$$\Delta OPL = \frac{dn_r}{dT} l\left[T(r,z,t) - T(0,0,t)\right] = \frac{dn_r}{dT}\frac{lT_0}{\gamma}\left[\exp\left(-2\frac{r^2}{\gamma\omega_e^2}\right) - 1\right], \tag{2}$$

where l is the length of the sample in the z direction, n_r is the refractive index, and $T(r, z, t)$ is the temperature with both radial and axial dependence. For expand the exponential in Eq. (2), we have used the approximation $r^2 << \gamma^2\omega_e^2/2$ with