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Influence of natural convection on beam propagation in fluidic optical device

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ABSTRACT

The fluidic optical device by means of the thermal lens effect has attracted increasing attention as a flexible beam shaper. However, onset of natural convection inhibits operation of the fluidic optical device as it causes asymmetric distortion on shaped beam profile. For implementation of the fluidic beam shaper, this adverse effect should be controlled in terms of the beam profile change. From this perspective, we investigated the influence of natural convection on the propagating beam profile through the fluidic optical device by means of CW laser induced the thermal lens effect. Numerical method taking advantage of beam propagation method was used to calculate modulation of the probe beam profile. The calculated results demonstrated good agreements with several experimental results. Using this numerical model, the parametric study to control asymmetry and quality of the annular beam was performed quantitatively in the dual beam thermal lens system. The core of this study is that the solution of the simple pentadiagonal equation can provide the crucial investigation on the modulation of the beam profile in the fluidic optical device with natural convection.

1. Introduction

After Gordon et al. [1] reported the transient and defocusing thermal lens effect of liquid, the thermal lens spectroscopy has been used for measurement of material properties with small absorbance. Several researchers [2–5] used the thermal lens spectroscopy to investigate linear thermo-optic properties using CW laser. Also, extensive studies [6–10] have been carried out to describe nonlinear optics of liquid using short and ultra-short pulsed lasers. With the progress of those works, the thermal lens effect has been understood in detail to derive many helpful theoretical models describing the thermal lens phenomena and modulation of the beam. In addition to these measurement researches, change of the beam profile itself is also of interest recently. Taking advantage of the thermal lens effect, we have developed the fluidic optical device as a flexible beam shaper [11–13]. One major characteristic of the fluidic optical device is that it can be used for both spatial and temporal laser beam shaping. Doan et al. [11,12] demonstrated the principle of the spatial beam shaper by means of the thermal lens effect and an application to Bessel beam generation system. In their study, it was confirmed that various beam profile could be easily obtained by controlling pump beam power. On the other hand, Kim et al. [13] reported temporal pulse-shaping technology of nanosecond-pulsed laser. From the result that pulse compression of 21.7% was achieved by their experiment, it was indicated that the thermal lens spectrometry can be applied for new oscillation mechanism of short-pulsed laser.

In those works, the thermal lens effect is utilized with various pump lasers for individual applications. The formation of the refractive index field significantly depends on optical parameters (such as CW or pulse, pulse width, power, beam waist, and configuration of absorbing sample). In particular, parameters such as pump beam power can be easily controlled without any change of the optical devices in many systems. Therefore, the fluidic optical devices have excellent flexibility as a beam shaper.

However, local absorption and heating inevitably results in large temperature gradient. Therefore, natural convection may occur in liquid medium and the convective flow brings out the distortion of the temperature field and refractive index field around the beam propagation axis. It leads to asymmetry of the beam spatial profile around the optical axis. Consequently, natural convection has an adverse effect on quality of the shaped beam. Akhmanov et al. [14] first investigated the thermal self-actions of laser beam, and several other works [15–17] provide theoretical studies on the onset of convection in transient regime. Most recently, Karimzadeh [17] demonstrated theoretical approach to

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Nomenclature

$\mathbf{v}$	flow velocity, (u, v, w), m/s	w_0	$1/e^2$ pump beam radius at focus, m
ρ	density, kg/m^3	λ_p	wavelength of probe beam, m
p	pressure, Pa	R_0	$1/e^2$ original probe beam radius, m
η	viscosity, kg/(s m)	W	$1/e^2$ probe beam radius, m
β	thermal expansion coefficient, 1/K	W_0	$1/e^2$ probe beam radius at focus, m
T	temperature, K	n	refractive index
g	gravity acceleration, m/s^2	n_0	refractive index at T_0
c_p	specific heat, J/(kg K)	E	electric field, N/C
κ	thermal conductivity, W/(m K)	$\hat{i}$	unit vector
h	heat transfer coefficient, W/(m^2 K)	j	imaginary unit
S	source term, W/m^3	k_0	free space wave number, m^{-1}
α	absorption coefficient, 1/m	I	intensity, W/m^2
x, y, z	coordinates, m	L	cuvette thickness
P_0	pump beam irradiation power, W	f	focal length of the lens
λ_e	wavelength of pump beam, m	z_R	Rayleigh length, m
r_0	$1/e^2$ original pump beam radius, m	M^2	beam quality factor
w	$1/e^2$ pump beam radius, m		

study transient self-phase modulation of a CW laser beam using Fresnel–Kirchhoff diffraction integral in the approximation of an optically thin absorbing medium. However, there are few reports on the behavior of propagating beam using numerical method. It must be conducted to evaluate quality of shaped beam profile with accuracy, in order to investigate the influence of natural convection for design of fluidic optical devices.

The objective of this study is to theoretically investigate and evaluate modulation of the beam profile through convective field in CW induced thermal lens system. In Section 2, the numerical approach to describe development of natural convection and the probe beam propagation are explained. In Section 3, experimental setup is represented to investigate modulation of the beam profile in the single beam system. In Section 4, experimental and theoretical results are demonstrated, and parametric study on quality of the shaped beam profile is conducted theoretically in the dual beam thermal lens system. The discussion will focus on modulation and distortion of annular-like profile, which attracts increasing attention for various applications [12,18,19].

2. Theory

2.1. Thermal lens system

Separation of the pump and probe beams is usually taken into account in order to obtain large change of the probe beam signal and flexibility on the thermal lens system. For the CW thermal lens system, refractive index change is predominated by temperature change. The probe beam experiences significant defocusing as liquid normally has negative value of dn/dT [8]. Schematic illustration of the thermal lens system used in this study is shown in Fig. 1. The ethanol-dye solution is used as a liquid sample because its dn/dT is large enough to conduct significant beam shaping. The beams parallel to ground are irradiated into the sample set parallel to the direction of the gravitational acceleration. The sample is filled in the glass cuvette with optical thickness L. Temperature field around optical axis is distorted upon the direction of the gravitational acceleration so that symmetry of the beam profile is also lost.

We used the Cartesian coordinates. The optical axis was set as z coordinates, and the direction of gravitational acceleration was matched with y direction.

2.2. Development of natural convection

Since temperature increase induced by CW laser absorption is only few several degrees of Kelvin, Boussinesq approximation can be used in the present context. The liquid sample and two walls of glass cuvette were set as calculation region as shown in Fig. 2. The calculation region on x-y plain was selected as 5 mm × 5 mm size square around the beam at the center as shown in Fig. 2(a) (size of the liquid sample on x–y plain: 24 mm × 30 mm). Thickness of glass cell was 1.5 mm (therefore calculating length on the z-direction was 4 mm, Fig. 2(b)). The governing equations are written as followings:

$$\nabla \cdot \mathbf{v} = \mathbf{0} \tag{1}$$

$$\rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla p + \eta \nabla^2 \mathbf{v} - \rho\beta(T - T_0)g \tag{2}$$

$$\rho c_p(\mathbf{v} \cdot \nabla)T = k\nabla^2 T + S \tag{3}$$

Eqs. (1)–(3) show the continuity equation, the conservation of momentum equation, and conservation of energy equation respectively. The glass wall was considered as no-slip wall, and the interface between the glass wall and ambient air was set as the natural convection boundary condition with 5 W/m^2 heat transfer coefficient. Also, as calculation region on x–y plain was selected around the beam, temperature boundary condition was set on four cross sections as $T = T_0$ as represented in Fig. 2(a). As the calculation region is large enough compared to beam radius, this temperature boundary condition can be applied to improve calculation performance.

Here, heating induced by CW laser is given as a source term S in Eq. (3). Considering Lambert–Beer law on propagating direction and the Gaussian intensity distribution, S can be written as following equation when the focal point of the beam is in the cuvette.

$$S = \alpha exp(-\alpha z) \times \frac{2P_0}{\pi w_0^2} exp\left[-2\frac{(x^2 + y^2)}{w_0^2}\right] \tag{4}$$

The source term, S, is expressed as a product of absorbing term and spatial intensity profile term. In fact, because the pump beam is focused, the beam radius and the intensity distribution of the beam vary in the cuvette. However, we did not reflect these axial effects because of the following reasons. First, as the cuvette thickness is very small (L = 1 mm) compared to the focal depth of the beam (116 mm), change of the beam radius in the cuvette is ignorable.