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Letters to the Editor

Thermal lensing compensation from composite CO_2-laser windows

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Laser beam defocusing and distortion which is referred to as thermal lensing can be produced in high-power CO_2 laser systems due to a window nonuniform irradiation. An analysis of thermal lensing compensation from composite windows is given. Isotropic materials and single crystals cut along [111] plane are considered.

1. Introduction

A nonuniform laser window irradiation in high-power CO_2-laser systems can produce a radial temperature gradient across the window that causes the window to bulge becoming thicker in the center. A temperature gradient in the refractive index is induced. As an added complication, the thermally induced stresses cause the refractive index to be different for different polarizations, that is a birefringence can be thermally produced. The resulting distortion and defocusing of the laser beam, which is referred to as thermal lensing has been studied for example in [1]–[5]. The distortion can be reduced by using a composite window consisting of two layers of transparent materials, one of which tends to diverge and the other to converge the laser beam [1], [5].

The purpose of this note is to analyse further the thermal lensing diminution in high-power CO_2 laser systems.

2. Basic formulae

Let us consider a Gaussian beam of amplitude $a(\rho,\theta) \sim \exp(-\alpha^2\rho^2)$ incident on a thin cylindrical window, where ρ is measured in units of the window radius. The thermal lensing of the laser beam transmitted through the window is determined by the aberration function $\Phi^{\rho,\theta}$ associated with the ρ and θ polarized waves. For a thin cylindrical window the aberration function takes the form [3], [4]

$$\Phi^{\gamma} = \rho_0 S_1^{\gamma}\overline{\Delta T} + 4\rho_0 S_2^{\gamma}\rho^{-2}\int_0^{\rho} dx\,\overline{\Delta T}x \tag{1}$$

where $\gamma = \rho$ or θ, $\overline{\Delta T} = \int_{-\eta_0}^{\eta_0} dz\Delta T(\rho,z,t)$, $\eta_0 = L_0/(2\rho_0)$, ρ_0 and L_0 are the window radius and thickness, respectively, z refers to the coordinate along the window thickness, ΔT is the temperature rise in the sample, and S_i^γ are the material parameter coefficients. For the small time case when $\Delta T \sim t$ one obtains [3]

$$\Phi^\gamma = C_1^\gamma \exp(-2\alpha^2\rho^2) + C_2^\gamma[1-\exp(-2\alpha^2\rho^2)]/(\alpha^2\rho^2) \tag{2}$$

where $C_i^\gamma = S_i^\gamma L_0 P_0 \beta t/c'$, P_0 is the laser beam peak power, β is the bulk absorption coefficient and c' is the specific heat.

The laser beam intensity I^γ at a prefocal point relative to the initial value I_0^γ in the absence of distortions is given by [5], [6]

$$I^\gamma/I_0^\gamma = 1-\tilde{\Delta}^\gamma, \tag{3}$$

with

$$\tilde{\Delta}^\gamma = k^2[\langle(\Phi^\gamma)^2\rangle - \langle\Phi^\gamma\rangle^2] \tag{4}$$

where k is the free space wave vector, and $\langle\,\rangle$ is defined as

$$\langle F\rangle = \int dSa(\rho,\theta)F/\int dSa(\rho,\theta), \tag{5}$$

the integral being taken over the window plane.

In the case of a single-layer window A of thickness L_A we obtained

$$\tilde{\Delta}_A^\gamma = (kP_0tL_A)^2\Delta_A^\gamma, \tag{6}$$

with

$$\Delta_A^\gamma = U(\alpha)[f_1^\gamma(A)]^2 + R(\alpha)[f_2^\gamma(A)]^2 + 2Q(\alpha)f_1^\gamma(A)f_2^\gamma(A) \tag{7}$$

where

$$f_i^\gamma(A) = \beta S_i^\gamma(A)/c', \tag{8}$$

$$U(\alpha) = f(5\alpha)/f(\alpha) - [f(3\alpha)/f(\alpha)]^2, \tag{9}$$

with

$$f(m\alpha) = [1-\exp(-m\alpha^2)]/(m\alpha^2), \tag{10}$$

$$R(\alpha) = \{E_1(\alpha^2) - 6E_1(3\alpha^2) + 5E_1(5\alpha^2) + f(\alpha) - 6f(3\alpha) + 5f(5\alpha) - [E_1(3\alpha^2) - E_1(\alpha^2)]^2/[\alpha^2 f(\alpha)]\}/[\alpha^2 f(\alpha)], \tag{11}$$

$$Q(\alpha) = \{E_1(5\alpha^2) - E_1(3\alpha^2) - [E_1(3\alpha^2) - E_1(\alpha^2)]f(3\alpha)/f(\alpha)\}/[\alpha^2 f(\alpha)] \tag{12}$$

where E_1 is the exponential integral [7].

For a thin composite of two layers A and B of thickness L_A and L_B, the aberration functions are additive, $\Phi^\gamma = \Phi^\gamma(A) + \Phi^\gamma(B)$, and one obtains

$$\tilde{\Delta}_{AB}^\gamma = (kP_0tL_A)^2\Delta_{AB}^\gamma, \tag{13}$$

with

$$\Delta_{AB}^\gamma = a_1^\gamma\chi^2 + 2a_2^\gamma\chi + a_3^\gamma \tag{14}$$

where

$$\chi = L_B/L_A, \quad a_1^\gamma = \Delta_B^\gamma, \quad a_3^\gamma = \Delta_A^\gamma, \tag{15}$$

$$a_2^\gamma = U(\alpha)f_1^\gamma(A)f_1^\gamma(B)+R(\alpha)f_2^\gamma(A)f_2^\gamma(B)+Q(\alpha)[f_1^\gamma(A)f_2^\gamma(B)+f_1^\gamma(B)f_2^\gamma(A)]. \tag{16}$$

As it was done in [5], we require the thickness ratio χ which minimizes Δ_{AB}^γ for a fixed thickness L_A

$$\chi_m^\gamma = -a_2^\gamma/a_1^\gamma. \tag{17}$$

For this value of χ one obtains

$$\Delta_{ABm}^\gamma = a_3^\gamma-(a_2^\gamma)^2/a_1^\gamma. \tag{18}$$

The sensitivity to variations of χ about χ_m^γ may be measured by the parameter η [5]

$$\eta = (1/2)|\partial^2(\Delta_{AB}^\gamma/\Delta_{ABm}^\gamma)/\partial(\chi/\chi_m^\gamma)^2| = |a_2^{\gamma 2}/(a_1^\gamma a_3^\gamma-a_2^{\gamma 2})|. \tag{19}$$

It can be noted that the relations obtained are quite different from those in [5].

3. Results

We have applied to above procedure for composite pairs of typical 10.6 μm window materials by supposing a unit length of material A and obtaining the value of L_B/L_A which minimizes Δ_{AB}^γ. The seven materials investigated are NaCl, KCl, KI, KBr, GaAs, ZnSe, and CdTe. The material parameters as given in [3], [4] are considered.

3.1. Isotropic materials

In case of isotropic materials the material parameter coefficients S_i^γ are given by [2]–[4], [8]:

$$S_1^\rho = \partial n/\partial T+\bar{\alpha}n^3[(1-\nu)p_{12}-\nu p_{11}]/2+\bar{\alpha}(1+\nu)(n-1), \tag{20}$$

$$S_2^\rho = \bar{\alpha}n^3(1+\nu)(p_{11}-p_{12})/8 = -S_2^\theta, \tag{21}$$

$$S_1^\theta = \partial n/\partial T+\bar{\alpha}n^3(p_{11}-2\nu p_{12})/2+\bar{\alpha}(1+\nu)(n-1) \tag{22}$$

where n is the refractive index, $\partial n/\partial T$ is taken at zero stress, $\bar{\alpha}$ is the linear thermal expansion coefficient, ν is Poisson's ratio and p_{ij}'s are elasto-optic coefficients.

Results are given in Table 1 for ρ-polarized waves. They are almost the same for θ-polarized waves. As one can see the composite NaCl–KI would result in substantially less lensing.

We obtained a strong dependence on the beam shape (α^2) as is shown in Table 2 for ρ-polarized waves for composite NaCl–KI. It is different from the relatively weak dependence on α^2 which is reported in [5].

3.2. Single crystals cut along [111] plane

For a single-crystal window whose plane is cut along [111] plane we obtained:

$$S_1^\rho = \partial n/\partial T+\bar{\alpha}n^3[(1-5\nu)p_{11}+(5-7\nu)p_{12}-2(1+\nu)p_{44}]/12+\bar{\alpha}(1+\nu)(n-1), \tag{23}$$

$$S_2^\rho = \bar{\alpha}n^3(1+\nu)(p_{11}-p_{12}+4p_{44})/24, \tag{24}$$

$$S_1^\theta = \partial n/\partial T+\bar{\alpha}n^3[3(1-\nu)p_{11}+3(1-3\nu)p_{12}+6(1+\nu)p_{44}]/12+\bar{\alpha}(1+\nu)(n-1). \tag{25}$$

Table 1. Aberration properties of composite windows at 10.6 μm for isotropic materials and $\alpha^2 = 1$

Composite (A–B)	L_B/L_A	Δ_{AB}/Δ_A	η
NaCl–KI	0.969	0.039	26.3
KI–GaAs	0.514×10^{-2}	0.304	4.29
KI–ZnSe	0.838×10^{-2}	0.500	3.00
KI–CdTe	0.570×10^{-1}	0.393	3.55

Table 2. Aberration properties of NaCl–KI composite at 10.6 μm as a function of α^2 for isotropic materials

α^2	L_B/L_A	Δ_{AB}/Δ_A	η
0.5	0.640	0.37×10^{-1}	28.0
1.0	0.969	0.39×10^{-1}	26.3
2.0	0.807	0.37×10^{-3}	2680.0

Table 3. Aberration properties of composite windows at 10.6 μm for [111] plane and $\alpha^2 = 1$

Composite (A–B)	L_B/L_A	Δ_{AB}/Δ_A	η
KBr–GaAs	0.137×10^{-3}	0.4×10^{-1}	0.26×10^{2}
KBr–ZnSe	0.201×10^{-3}	0.7×10^{-4}	0.14×10^{5}
KBr–CdTe	0.146×10^{-2}	0.2×10^{-1}	0.44×10^{2}
KCl–GaAs	0.476×10^{-2}	0.8×10^{-1}	0.13×10^{2}
KCl–ZnSe	0.689×10^{-2}	0.6×10^{-2}	0.17×10^{3}
KCl–CdTe	0.508×10^{-1}	0.6×10^{-1}	0.18×10^{2}
KI–GaAs	0.648×10^{-2}	0.2×10^{-2}	0.52×10^{3}
KI–ZnSe	0.985×10^{-2}	0.3×10^{-1}	0.38×10^{2}
KI–CdTe	0.699×10^{-1}	0.1×10^{-4}	0.93×10^{5}

These formulae are different from those given in [5]. Results are shown in Table 3 for ρ-polarized waves. A wider variety of appropriate pairs for composites there is with excellent improvements, by as much as several orders of magnitude, comparing to izotropic materials.

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Компенсация термического линзинга, происходящего из сложных окон лазера CO_2

Расфокусирование, а также дисторсия, называемые здесь совместно термическим линзингом, могут возникнуть в лазерных системах CO_2 большой мощности вследствие неоднородности облучения окна. Дан анализ компенсации термического линзинга, происходящего из окон. Рассуждены изотропические материалы, а также монокристаллы, срезываемые вдоль плоскости [111].

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