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Thermal lensing in diode-pumped [001]-cut tetragonal crystals

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ABSTRACT

Thermal lensing is theoretically studied for laser discs from [001]-cut tetragonal crystals under the plane stress approximation, considering anisotropy of their elastic and photo-elastic properties. Analytical description of the stress-induced birefringence is presented. This allows us to derive analytical expressions for the photo-elastic term χ'', "generalized" thermo-optic coefficient (TOC), sensitivity factors of the thermal lens and its astigmatism degree, as well as discuss orientation of the principal meridional planes of the lens. These parameters are determined for the discs from tetragonal scheelite-type molydbate crystals, Nd:$PbMoO_4$, Nd:$CaMoO_4$ and Nd:$NaBi(MoO_4)_2$ at ~1 μm. It is shown that the photo-elastic effect plays an important role in the formation of the thermal lens for tetragonal crystals, and χ'' value can be either positive or negative. We also predict theoretically that for anisotropic crystals the orientation of the principal meridional planes of the thermal lens is not linked to the polarization direction.

1. Introduction

Thermal lensing is known to be one of the most important limitations for power scaling capabilities of diode-pumped solid-state lasers (DPSSL) [1]. Under diode pumping, a complicated pattern of thermo-mechanical [2,3] distortions is formed in the laser element. For a light beam passing though such an element, these distortions can be expressed in terms of the variation of the optical path length [4]. It has been recognized that for longitudinal diode pumping, this variation has parabolic dependence on the radial coordinate that corresponds to a lens-like behaviour of the laser element. The key parameter of the thermal lens is the optical (refractive) power D. It is determined as inverse of the focal length, $D=1/f$. In contrast to a conventional lens, the thermal lens is pump-dependant, i.e. its optical power is scaled accordingly to the increase of the absorbed pump power [4].

Thermal lens vary the stability conditions of the laser cavity [5], mode-matching conditions for pump and laser beams [6] and polarization state of the laser beam [7]. Influence of a relatively weak thermal lens can be detected as a drop of the laser power, distortion of an output laser beam [8], polarization-switching [9] or depolarization loss. Strong thermal lens can in general lead to an instability of the laser cavity and thus to laser ceasing (that occurs at some critical value of D_{th} [10]). As the optical power is proportional to the pump level, pumping of DPSSL is limited by the point where optical power reaches the critical value D_{th}. However, there are few laser schemes where the action of the thermal lens is beneficial. For instance, positive thermal lens (i.e., with $D>0$ that means focusing action) can provide the desired mode stabilization in the plano–plano cavity of a microchip laser [11]. Switching of the polarization state can lead to a dual-wavelength regime of laser operation.

It is thus recognized that proper characterization of the thermal lens is crucial for laser engineering. To derive expression for the optical power of the thermal lens, one should consider three effects, namely (i) temperature dependence of the refractive index that is expressed by a thermo-optic coefficient (TOC), dn/dT, (ii) photo-elastic effect, or variation of the refractive index induced by thermal strains and (iii) end-bulging of the end surfaces of the laser element caused by a non-uniform thermal expansion [4]. The action of the above mentioned three effects is summarized in the so-called "generalized" TOC, $\chi=dn/dT+\chi''+\chi'$ where χ'' is the photo-elastic term and χ' is the end-bulging term [4]. The value of dn/dT for the laser material is measured directly. To determine the χ'' and χ' terms, one should find thermally induced strains and stresses, as well as their influence on the optical indicatrix of the laser material (i.e., to describe the stress-induced birefringence) [12]. In an analytical form, this has been performed for laser discs from isotropic and high-symmetry (cubic) materials [4,13]. Recently, the first part (derivation of thermal stresses and strains) was also done for the discs from tetragonal crystals [14,15].

In the present paper, we aimed to describe analytically the stress-induced birefringence in the laser disc from any tetragonal crystals with a particular cut along the [001] axis. This allowed us to determine analytical expressions for the photo-elastic term χ'', "generalized" TOC, sensitivity factors of the thermal lens and its

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astigmatism degree, as well as describe orientation of the principal meridional planes of the thermal lens. It is important to note that this analytical solution was obtained considering the anisotropy of elastic and photo-elastic properties of the tetragonal crystal. Such an analytical study for laser discs from tetragonal crystals has been never performed before. Due to the availability of the material parameters, we used the derived analytical expressions to characterize thermal lens in three tetragonal sheelite-type molybdates, $Nd:PbMoO_4$, $Nd:CaMoO_4$ and $Nd:NaBi(MoO_4)_2$. These crystals were intensively studied for the use in DPSSLs with Raman self-conversion [16,17].

2. Physical model

We consider a tetragonal laser crystal. The shape of the laser element from such a crystal is a disc; its thickness, L, is substantially lower than the radius, r_0. The dependence of all physical values on the axial coordinate, z, is ignored (they are considered as averaged over the L length). The axis of the disc is parallel to the [001] crystallographic axis (c-cut disc), so [100] and [010] axes are lying in the disc plane. The crystal is diode-pumped. The heat release in the crystal is related only with a thermalization of a part of an absorbed pump power. Pumping is longitudinal, pump beam is "top-hat", the pump spot radius $w_p = r_0$. Cooling is provided from all lateral sides of the disc; and its boundary is free of external forces. A steady-state heat problem is considered. Pump divergence is not taken into account due to a small thickness of the disc. Absorption saturation (that depends on the saturation intensity of the optical transition) is not considered. For the thermo-mechanical description of the disc, we use the so-called *plane stress* approximation [4] that means zero axial stress, $\sigma_z = 0$.

Under the described conditions, the temperature distribution in the plane of the disc is parabolic [2]:

$$T(r) = \Delta T\left(1 - \frac{r^2}{r_0^2}\right), \quad \text{where } \Delta T = \frac{\eta_h P_{abs}}{4\pi\kappa L} \tag{1}$$

Here, P_{abs} is the absorbed pump power, η_h is the fractional heat loading (part of P_{abs} that is dissipated as heat), κ is the thermal conductivity in the disc plane, ΔT is the temperature rise in the center of the disc ($r = 0$) with respect to its boundary.

For the described laser disc with a parabolic temperature distribution in accordance with Eq. (1), optical power of the thermal lens D is determined as following [4]:

$$D_{A(B)} = \frac{\eta_h P_{abs}}{2\pi\kappa w_p^2}\left[\frac{dn}{dT} + \chi''_{A(B)} + \chi'\right] \tag{2}$$

The notations A(B) refer to the principal meridional planes of the thermal lens. Meridional plane is a plane that contains the direction of light propagation k (the disc axis) and some direction in the disc plane, Fig. 1. Among the all possible meridional planes, there are only two mutually orthogonal planes corresponding to the maximum and minimum refraction (optical power of the lens). They are called the principal ones. Following state-of-the-art studies of thermal lens in isotropic and high-symmetry (cubic) materials, we can formally represent the χ'' and χ' terms as following [4,13]:

$$\chi''_{A(B)} = \alpha n_0^3 Q_{A(B)} \tag{3a}$$

$$\chi' = (1 + \nu^*)(n_0 - 1)\alpha \tag{3b}$$

Here, α is the thermal expansion coefficient, n_0 is a refractive index of an unpumped crystal, $Q_{A(B)}$ are the so-called photo-elastic constants. Parameter ν^* indicates the contribution of end-bulging

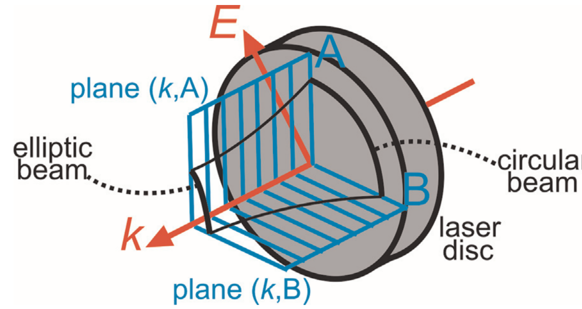

Fig. 1. Introduction of the principal meridional planes of the thermal lens for a laser disc: k – light propagation direction, E – light polarization, A and B denotes directions in the disc plane corresponding to the maximum and minimum refraction.

effect that occurs due to the thermal stresses (in contrast to the part that originates solely from the thermal expansion) [15]. For isotropic materials, this parameter is equal to the Poisson ratio, $\nu^* \equiv \nu$ [4].

Thus, the expression for the "generalized" TOC is the following:

$$\chi_{A(B)} = \frac{dn}{dT} + \alpha n_0^3 Q_{A(B)} + (1 + \nu^*)(n_0 - 1)\alpha \tag{4}$$

The key parameters for the description of the thermal lens in a diode-pumped crystal are the sensitivity factor M and the astigmatism degree S. The M-factor shows the variation of the optical power of the thermal lens due to 1 W variation of the absorbed pump power and it is usually expressed in $m^{-1} W^{-1}$. It is determined as [18]:

$$M_{A(B)} = \frac{dD_{A(B)}}{dP_{abs}} \tag{5}$$

The difference of the sensitivity factors for the principal meridional planes A(B) is called the astigmatism degree [19]. It can be expressed in two ways [9,19]:

$$S = |M_A - M_B| \tag{6a}$$

$$S = \frac{|M_A - M_B|}{M_{max}}. \tag{6b}$$

Within the first definition, S is also expressed in $m^{-1} W^{-1}$. In the second case, S is determined in percents. The astigmatism degree is zero for a spherical lens (no astigmatism) and it equals 100% for a purely cylindrical lens. For a c-cut tetragonal crystal, the S value is determined solely by the photo-elastic effect.

For any tetragonal crystal, dn/dT coefficients can be measured directly. Analytical expression for the end-bulging term χ' for any c-cut tetragonal crystal was derived in [14,15] using the method of Airy stress function [20]. However, analytical expressions for the photo-elastic term χ'' and, more specifically, for the photo-elastic constants $Q_{A(B)}$ have been never derived for laser discs from tetragonal crystals. In the present paper, we aimed to describe analytically the stress-induced birefringence in the laser disc from any c-cut tetragonal crystals. This allowed us to determine analytical expressions for the $Q_{A(B)}$ constants and, thus, to derive a complete expression for the "generalized" TOC that is required for the calculation of main parameters of the thermal lens (M, S). Consideration of the stress-induced birefringence is also crucial for understanding the orientation of the principal meridional planes of the thermal lens A(B).

3. Results and discussion

All tensor quantities for any anisotropic crystal are normally