EXPERIMENT AND NUMERIC SIMULATION OF THE INDUCED TERMOELASTIC DISTORTION IN DIODE END PUMPED BIREFRIGENT LASER CRYSTALS.

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Introduction

With laser diodes, it is possible to use especial pumping geometries. In particular the end-pumping scheme enables one to achieve excellent overlap between the spatial-mode of the pump laser and the cavity-mode, which is especially helpful in single-mode operation, and reduces optical distortion. Although high optical efficiency is achieved, there remains an expressive parcel of pumped power, which is converted into heat.

The non-uniform heating of the active medium generates mechanical stress and optical distortion. In high power solid-state laser, these thermal problems are dominant. The thermal stress fracture is the upper limit when increasing power of the pump laser. Also, the ability to forecast the induced optical distortions is very important for any serious resonator project.

In this paper we analyze the induced optical distortion in a Nd:YLF crystal pumped by a laser diode. The crystal has a slab geometry with the pumped face cut at Brewster angle. The pumping scheme is longitudinal, and the laser diode is a one-dimensional array of 24 emitters, with dimensions of 1 cm x 1 micron and with emitting wavelength of λ=792 nm. The electric field of the pump beam is parallel to the emitters and is aligned along the crystal c-axis.

The temperature and stress fields inside the crystal are calculated by the finite element method. After this calculation, the optical path difference (OPD) induced by the temperature and the displacement fields is calculated for the two possible beam polarizations (π e σ) of an analyzing beam. The calculated OPD is compared with the experimentally measured OPD in a double-pass Twyman-Green interferometer.

Theory and Model Description

For the numerical simulation, the crystal geometry is approximated by a slab without the Brewster angled facets. The dimensions of the crystal are 6x2x10mm in the x,y and z direction. The pumping beam propagates in the z direction and is focalized at the z=0 crystal face. The generated heat in the crystal is removed by forced cooling on the two opposed crystal sides with coordinates y=0 and y=2 mm. The other two sides are considered isolated, as shown in figure 1. The pumping beam is highly asymmetric. We measured an elliptic profile of w_{ox}=1250µm and w_{oy}=50µm at the focus and beam quality parameters of M_x^2=2000 e M_y^2=3 by means of a CCD-camera with specialized software. The total power emitted by the diode is 10W throughout all the experiments.

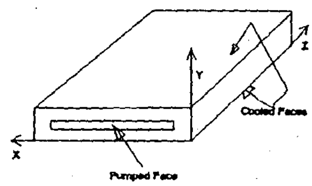


figure 1: Orientation of the pumped crystal.

The optical distortion are calculated after the calculus of temperature and displacement field. The first calculated field is temperature field T(x,y,z) by the solution of stationary thermal diffusion equation, $k\nabla^2 T(x,y,z)=Q(x,y,z)$, where K is the thermal conductivity and Q(x,y,z) is the a thermal power source. The power density Q(x,y,z) has the same profile of intensity of absorbed pumping beam and it is showed in (1). Po=3W is portion of the pumping power transformed in heat, and α=800m^{-1} is optical absorption coefficient of the sample of Nd:YLF. The boundary condition are T=0 for the cooled faces (ideal cooling), and KdT/dn=0 for the isolated faces, dT/dn is the power flux across this faces.

$$(1)\quad Q(x,y,z)=\frac{2\alpha P_o}{\pi\omega_x(z)\omega_y(z)}e^{-2\left(\frac{x^2}{\omega_x^2(z)}+\frac{y^2}{\omega_y^2(z)}\right)-\alpha z}$$

Thermal diffusion equation is calculated by finite elements methods [1], with the active medium approximated by one mesh of 11x11x11 points, with a total of 1000 three-dimensional linear elements with 8 nodes each. The solution convergence is accelerated by increase of mesh density in region near the pumped region,

The displacement field is calculated using the equilibrium equation for the stress tensor $\partial_i \sigma_{ij}=0$ [1c2]. This equation is represented as a function of the strain tensor ε and assumes the form of equation (2) [1], where **D** is the elastic modulus tensor, and ε_0 is the strain tensor due the thermal expansion. In equation (3) the strain tensor is represented as a function of the displacement **u**, of the material points, and **E** is thermal expansion tensor of the material (Handbook of Optics [4]). Finally, the equation (2) is calculated as a function of the displacement **u** by the finite elements methods [1], similar to the thermal diffusion, using the temperature field calculated by the diffusion equation. The boundary conditions are $\sigma_{ij}n_j=0$ on all the crystal faces, i.e. the boundary is free for expansion, without external tension on the boundary (n_i is the unitary vector normal to the surface).

After obtaining the displacement field, the stress and strain fields are calculated by relation $\sigma_{ij}=D_{ijkl}(\varepsilon_{kl}-\varepsilon_{0kl})$.

$$(2) \qquad \frac{\partial \sigma_{ij}}{\partial x_i}=\frac{\partial}{\partial x_i}D_{ijkl}\left(\varepsilon_{kl}-\varepsilon_{kl}^{0}\right)=0$$

$$(3) \quad \varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right) \text{ and } \varepsilon_{ij}^{0}=E_{ij}T$$

The induced optical path difference is obtained by equation (4) [3], valid only for beams with small divergence. In equation (4) n is the refractive index, $\partial n/\partial t$ is the thermal optical dispersion and l is the length of the active medium. To calculate the stress induced variation of the index of refraction, which also contributes to the OPD, one needs the photo-elastic coefficients, which are not available in literature so far. Due to the natural birefringence of YLF this contribution is negligible.

The total OPD is a result of the sum of the effects of temperature and displacement fields.

(4)

$$OPD=\int\left[\frac{\partial n}{\partial T}T(x,y,z)+(n-1)\frac{\partial u(x,y,z)}{\partial z}\right]dz$$

The Nd:YLF crystal belongs to the C_{4h}^{6} point group and therefore is birefringent, which means that it has different refractive index and dispersion along the a-axis and c-axis. This means that the final OPD depends on the polarization of the laser beam, with effective thermal lenses different for the π and σ polarization.

Interferometric Measurements and Simulation

The experimental verification of the induced OPD is measured by a Twyman-Green interferometer shown in figure 2. The interferometer is mounted on a vibration free table generating very stable interferograms. A piezoelectric micrometer acts on one of the mirrors, enabling to control the overall phase. The measurements are realized with the probe beam, once along the c axis (π polarization) and then along the other axis (σ polarization). The probe beam passes across the sample twice and therefore the fringe separation is half the HeNe laser wavelength (316 nm). The images are captured by a CCD camera. Using the software supplied with the CCD we subtracted the interference fringe pattern of the unpumped sample from the interference pattern of the sample under diode pumping. The obtained image is therefore free of OPD due to any other influences than the pump beam.

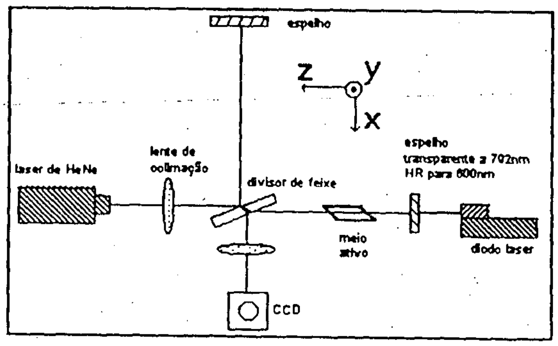
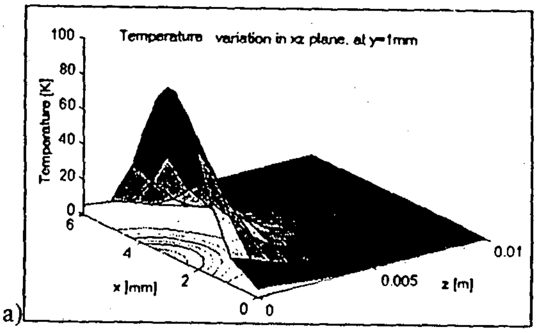
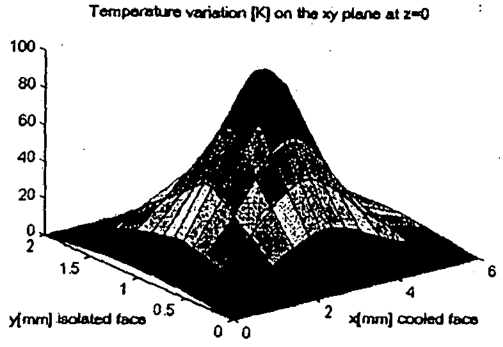


figure 2) Experimental setup of the Twyman-Green interferometer.

The figures below show the results obtained by the simulation. Looking at figure 3 a) and b), we can see that the increase in temperature is concentrated near the pumped surface and tends to zero near the other surfaces. The maximum temperature variation is 94K, at the center of the pumped surface.

a)




b)

figure 3-a) Temperature variation inside the xz plane at y =1mm and b) inside the xy plane at z=0. The pump beam is focalized at z=0. The maximum temperature variation is 94K.

The figure 4 shows the stress distribution in the yz-plane at the middle of the crystal (for x equal to 3 mm) which is equal to the tension along the x direction. The center of the crystal is in a compressed state (negative values of stress), while the crystal facet is under tension. This is due to the fact that the cold crystal surface hinders the hot crystal center from expanding. The highest stress value of 32 Megapascal occurs on the cooled surface being the strength limit of YLF only 35 Megapascal, which means that the crystal is close to its fracture limit (we actually fractured two crystals).

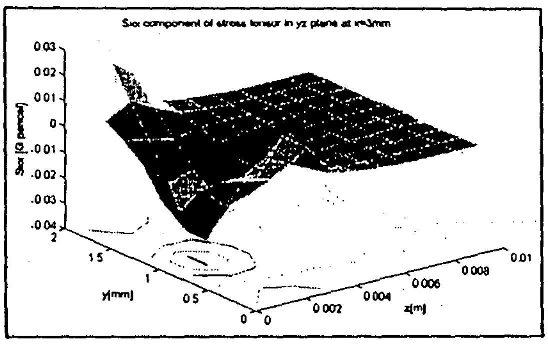


figure 4- Sxx component of stress tensor in yz plane (along the pump beam) at x=3mm. Negative means compression and positive means tension.

The optical distortion induced by the temperature and displacement fields together are analyzed by means of the OPD. The simulations are shown in figure 5 and figure 7. The experimentally measured OPD are shown in figure 6 and figure 8. Thermal OPD in the π-direction are shown in the first set of figures. In this case the probe beam is in the π electric field polarization.

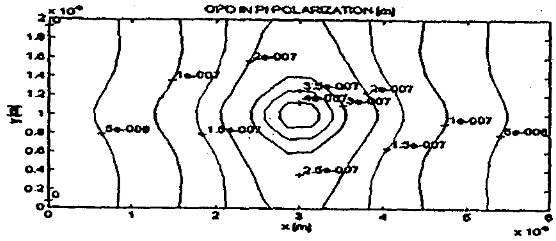


figure 5) Calculated temperature and displacement induced OPD. The center to edge OPD, is ≈420 nm in the x-direction, and ≈220 nm in the y-direction.

figure 6) Measured OPD in the π-direction. The mean OPD (center to edge) in x direction is ≈470 nm, while the y direction is in between 170 nm and 290 nm. Clearly observable is a white interference fringe around the center.

In this second set of figures the probe beam has σ-electric field polarization.

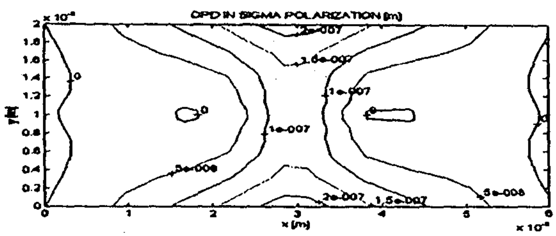


figure 7) Temperature and displacement induced OPD. The center to edge OPD, is ≈110 nm in the x-direction, and ≈90 nm in the y-direction.

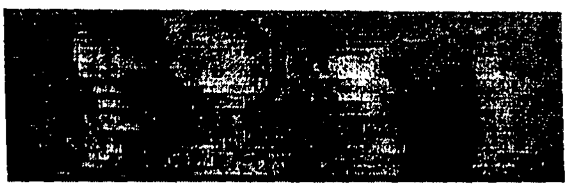


figure 8) Measured OPD in the σ-direction. The OPD between black and white areas is between 100 and 150 nm.

Conclusions

We obtained good agreement between experimental and calculated data. Specially for the π-polarization, which is the commonly used direction of polarization in YLF lasers, the agreement is within 12 % of error. The slight asymmetry in the x-direction can be explained by the Brewster angle cut of the crystal.

The σ-polarization shows a bigger variation between experimental and calculated OPD values. This discrepancy is currently subject of study in our team. However the simulated OPD profiles agree very well with the experimentally obtained pictures.

For the π polarization the thermal lens is positive and elliptical. However, for σ polarization, the lens has a more complex form: negative in the y-direction and positive in the x-direction.

Most important for our studies is the fact that the induced stress component S_{xx} has a very high value of 32 MegaPascal which easily fractures the crystal. Our goal is now to optimize the pumping and cooling scheme in such a way that we obtain reliable lasers with stress components much below 32 Mpascal.

Acknowledgments

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Experiment and numerical simulation of the induced termoelastic distorsion in diode in pumped birefrigent laser crystals

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