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Thermal effects reduction in a diode side-pumped rod-like bonded α-quartz||Nd:glass||α-quartz amplifying medium

Thomas Dubé[1,*], *Patrice* Camy[2], and *Sébastien* Montant[1]

[1]CEA CESTA, 33114 Le Barp, France
[2]CIMAP, ENSICAEN, UMR 6252, 6 boulevard du Maréchal Juin, 14050 Caen Cédex, France

Abstract. We present a numerical study of a square-shape rod-like bonded laser gain medium operating at 1053 nm. The sample is composed of a 5-mm thick Nd-doped phosphate glass bonded to two α-quartz crystals. Owing to this face cooling scheme, the heat generated in the gain medium is effectively reduced, hence resulting in less optical distortions. The simulation of the thermomechanical effects was conducted using COMSOL MultiPhysics® software. Transverse wavefront distortion and birefringence profiles were computed for a given pump mean power. Wavefront and birefringence measurements will be conducted on the bonded sample using a pump-probe setup which is discussed in this paper. These measurements will be presented and weighed with the numerical results.

1 Context of the study

High-power laser facilities, such as the National Ignition Facility (NIF, United States) and the Laser MegaJoule (LMJ, France), rely on Nd-doped phosphate glass for amplification of each laser beam at 1053 nm. The combination of the flash-lamp pumping scheme with the low thermal conductivity of the laser glass leads to strong thermal effects in the amplify medium, resulting in wavefront distortion and stress-induced birefringence [1]. In particular, the large-aperture glass rod of the multi-pass amplifier stage in the LMJ front-end limits its overall performance down to 1 J every 5 minutes.

We investigate the application of bonding to reduce the thermal effects generated in the gain medium. Face-cooling scheme has been demonstrated for heat reduction purposes using sapphire and diamond crystals bonded to Nd:YAG crystals [2,3]. The present work focuses on the reduction of the thermal load in a diode-pumped 5-mm thick LG770 laser glass bonded to two α-quartz crystals.

In what follows, we describe the numerical model conducted using COMSOL MultiPhysics® and the wavefront and birefringence characterisation setup.

2 Numerical model

2.1 Formulation of the problem

The absorbed pump energy contributes to the amplification and the heat source $Q(x,y,z,t)$ due to non-radiative transitions. We assume a temperature continuity at each area of contact between the glass and each quartz crystal. The heat generated during pumping propagates in the gain medium ($i = A$) and the heatsinks ($i = HS$). The Fourier heat equation is expressed as [1,4]:

$$\rho_i C_{p,i} \frac{\partial T_i}{\partial t} - K_{th,i} \nabla T_i = Q_i, \qquad i = A, HS \qquad (1)$$

Where T, ρ, C_p and K_{th} are respectively the temperature the mass density, the specific heat and the thermal conductivity. Q_i is zero in the crystals (HS).

Stress occurs due to local thermal expansion and compression of the material sustaining the temperature rise. Using Hooke's law, mechanical stress is derivated from the temperature field. Temperature and mechanical stress increments give rise to a local change of the refractive index. The refractive index tensor in an isotropic material (e.g. the laser glass) under thermal stress writes [1,4]:

$$\bar{\bar{n}} = \left[n_0 + \frac{dn}{dT}(T - T_0)\right]\bar{\bar{I}} - \frac{n_0^3}{2}\overline{\overline{\Delta B}} \qquad (2)$$

Where n_0 is the unperturbed refractive index at 1053 nm, $dn/_{dT}$ is the thermo-optic coefficient, T_0 is the cooling temperature, $\bar{\bar{I}}$ is the identity matrix and $\overline{\overline{\Delta B}}$ is the second-rank impermeability tensor altered by the photo-elastic effect. It is derivated from the tensor product of the material-dependant piezo-optic tensor with the computed mechanical stress tensor [1]. This expression enables a numerical evaluation of both birefringence and optical path difference (OPD) during pumping.

2.2 Numerical model

We perform a finite element study with COMSOL MultiPhysics® to consecutively solve (i) the heat equation and (ii) the mechanical stresses in the amplifying medium before (iii) evaluating the refractive index.

* Corresponding author: thomas.dube@cea.fr

Afterwards, (iv) a wavefront calculation is performed using the ray optics module a single pass through the rod.

The 5-mm thick gain medium is made of Nd-doped phosphate LG770 glass $(5 \times 10 \times 10\ mm^3)$. Each transverse surface is bonded to a $\vec{c}$-oriented α-quartz crystal $(10 \times 10 \times 10\ mm^3)$ as illustrated in Fig. 1. Optical quartz benefits from a higher thermal conductivity (K_{th}) than LG-770 while matching both Coefficient of Thermal Expansion (CTE) of the glass in the transverse plane (perpendicular to $\vec{c}$-axis) as described in Table 1. The gain medium is side-pumped by diodes emitting at 800 nm with a total mean pump power of 2 W.

Table 1. Key parameters of both LG-770 (supplied by Schott) and α-quartz (supplied by Sawyer Technical materials).

Materials	K_{th} (W.m^{-1}.K^{-1})	CTE (10^{-6} K^{-1})	n_0
LG770	0.57	13.36	1.499
α-quartz ⊥ $\vec{c}$	6.21	13.37	n_o = 1.534
α-quartz // $\vec{c}$	10.7	7.97	n_e = 1.543

For comparison purposes, we perform the same simulations on two control samples: a single 5-mm thick LG-770 piece and a 25-mm long LG-770 rod with equivalent transverse dimensions. Each sample is illustrated alongside first numerical results in Fig. 1.

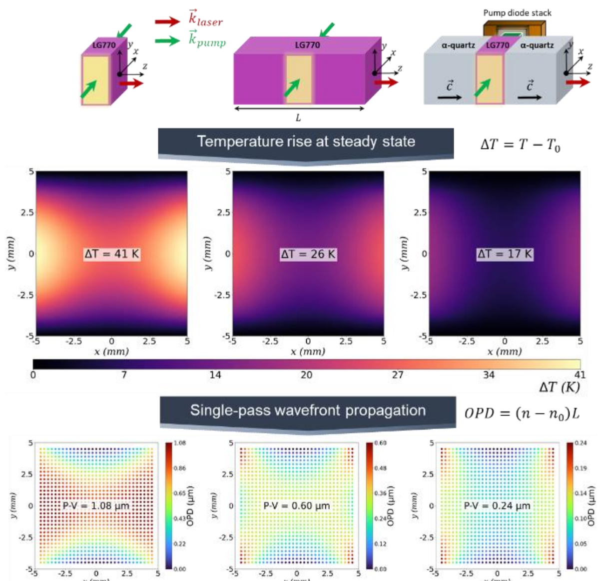

Fig. 1: (Color online) (Top) Sketches of the bonded structure and the control samles. (Middle) Temperature profiles at the center of each gain medium at steady-state. (Bottom) Resulting distorted wavefront after a single-pass.

Owing to the face-cooling scheme, the temperature in the gain medium is respectively decreased by 63% and 35% against both 5-mm and 25-mm long LG-770 rod as shown in Fig 1. (middle). The bottom profiles in Fig. 1 highlight a flattened wavefront with a 5-times lower OPD (left) as compared to the single LG-770 piece (right).

3 Characterization of the bonded sample

The samples are prepared by Onyx Optics Inc. (United States) and Cristal Laser (France) using different methods. The former uses its Adhesive-Free Bonding® method [5] and the latter applies a transparent adhesive layer between the materials [6]. A single-pass pump-probe setup for our measurements is described on Fig. 2.

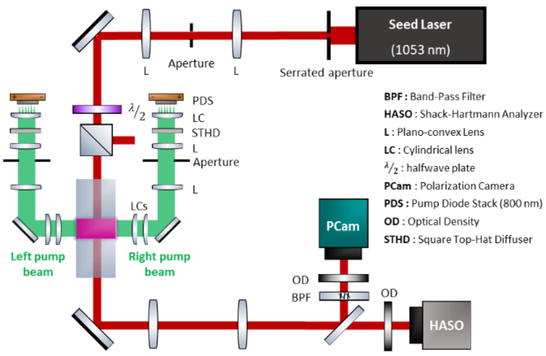

Fig. 2: (Color online) Sketch of the experimental setup. The probe beam is illustrated in red and the pump ones in green.

The sample is maintained with water-cooled copper clamping jaws. We use a regenerative cavity delivering 10 mJ at 1053 nm at 1 Hz repetition rate as the seed laser. The probe beam is shaped into a 8-mm large square profile using a serrated aperture. Then, the beam is transported at the centre of the sample with the help of an afocal system. The medium is pumped on each side by a diode stack using a spatial beam shaping system, which enables the control of both beam size and homogeneity. Its principle hinges on imaging the far field of the pump profile diffused by a square top-hat diffuser (STHD). Both wavefront distortion and birefringence are measured with the help of a Shack-Hartmann wavefront sensor (HASO) and a polarization camera (PCam). Finally, we plan to add a thermal imager for live temperature monitoring.

4 Conclusion

We present a bonded Nd-doped glass||α-quartz rod-like gain structure. First, we conducted a numerical study of both temperature rise and thermal stress in the sample. Then, the wavefront distortion after a single pass is estimated by computing the refractive index variations under thermal stress. The pump-probe characterization setup is also presented. Wavefront and birefringence measurements will be compared to our model.

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