Comparison of absolute temperature measurements in diode-end-pumped laser crystals with FEA simulations

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Abstract: We are presenting a comparison between high resolution absolute temperature mapping on the surface of diode-end-pumped laser crystals using non-contact infrared measurements and results of Finite Element Analysis (FEA) using a semi-unstructured discretization grid.

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1. Introduction

Reliable analysis of thermal effects in laser crystals is very important for the development of diode-pumped solid-state lasers. Mode structure, beam quality, laser output power etc. are influenced by thermal lensing. Temperature induced stress causes depolarization and even fracture of the crystal [1]. At the ASSP 2004 one of the authors of the present paper, François Balembois, together with coworkers presented a new method to generate high resolution temperature mapping by carrying through direct absolute measurements at the surface of a diode-end-pumped Yb:YAG crystal [2]. So far only indirect thermo-optical methods have been reported involving more or less known thermo-optical coefficients. However, since measurements are time-consuming and moreover not only the temperature distribution at the surface but much more the 3D temperature distribution inside the crystal is responsible for the behavior of the laser, we decided to cooperate in a research project using this new measurement technology to verify the results of a Finite Element Analysis (FEA) code developed especially for laser cavity analysis by two of us, Konrad Altmann and Christoph Pflaum [3]. Comparison between measurement and results of simulation has been carried through for Nd:YAG 1 at. % and Nd:YVO_4 1 at. %. Agreement turned out to be very good.

2. Experimental Setup

The non-contact absolute measurements are performed with an infrared imager working in the 8-12 µm spectral range. The experimental setup is presented on figure 1. The pump source was a high power fiber-coupled diode array (THALES Laser diode) emitting up to 30 W at 968 nm. The fiber had a core diameter of 800 µm and a numerical aperture of 0.22. The pump beam was focused on Nd-doped crystals via two doublets. The pump spot diameter varied from 800 µm to 1300µm (depending on the experiments). The high spatial resolution of the thermal imager was obtained thanks to a dichroic Zinc selenide plate, High Reflectivity (HR) coated for 800-1000 nm on one face (at 45° angle of incidence), and also coated for High Transmission (HT) in the 8-12 µm spectral range on both faces (coating from *Opticoat Inc.*). An aberration-free germanium objective (focal length 50

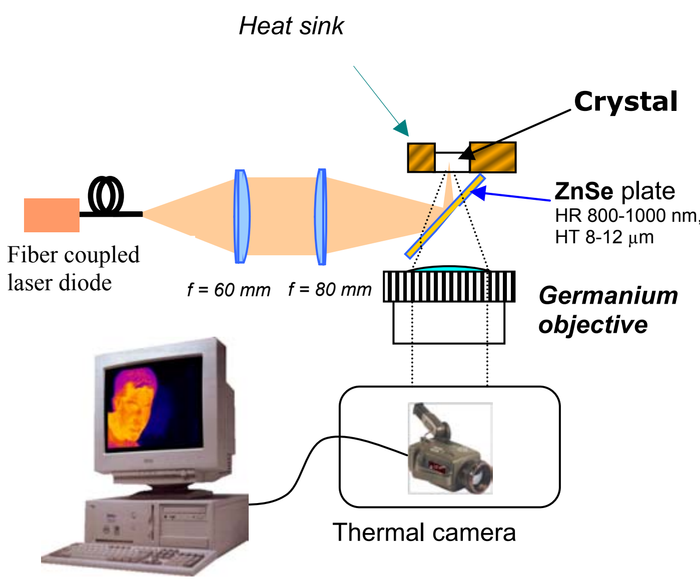

Figure 1. Experimental Steup

mm, N.A. 0.7) was appended close to the ZnSe plate to create the intermediate thermal image. The camera was an AGEMA 570 (*Flir Systems Inc.*) consisting of 240x320 microbolometers working at room temperature. The accuracy of the temperature measurements was about 4% for all the system. The numerical aperture of the whole imaging system in the object medium was around 1, a theoretical spatial resolution of 10 µm could be achieved; however, the resolution is limited here to 60 µm by the size of the pixels. The crystal was clamped in a copper block by its four side faces. The heat is being removed from the copper block by a flow of circulating water.

3. Finite Element Analysis

To solve the differential equations for thermal and structural analysis (thermal deformation), we applied a finite element discretization on semi-unstructured grids [4] that have properties which are very useful in the application of laser simulation:

- Semi-unstructured grids calculate temperature distribution and deformation on a structured grid inside of the crystal which is very well suited for the analysis and interpolation of the data in a subsequent optical analysis of the cavity. This structured grid is connected to the surface of the crystal by small irregular elements.
- Semi-unstructured grids allow using fast computational codes. Different from irregular meshing computational time increases linearly with the number of grid points.
- Semi-unstructured grids can be stretched in x-, y-, and z-direction.
- High accuracy can be achieved by the use of small mesh size.
- The super-convergence of the gradient inside of the domain leads to an accurate approximation of the stress.

Our code is implemented in the laser simulation program LASCAD [5] and accessible from an easy-to-use GUI. In the present case, heat load distribution has been approximated by the use of a gaussian beam in combination with an absorption coefficient. Boundary conditions have been defined by keeping the lateral surfaces of the crystal on constant temperature.

4. Comparison between measurements and simulation

In this paragraph we are reporting results of experiment and computation for Nd:YAG 1 at. % and Nd:YVO_4 1 at. % rectangular crystal blocks being end pumped by a fiber-coupled diode array as described in sect. 2. The pump beam profile was gaussian. Crystal dimensions and pumping scheme are described by the following parameters:

The dimensions of the Nd:YAG 1 at. % block were the followings: length : 4 mm, width = height : 2 mm.
The absorption coefficient of the Nd:YAG crystal was about 4.7 cm^{-1}.

The parameters of the pump beam which has been focused into the crystal from one end were the followings:
beam diameter at focus: 1300 µm, distance of focus from entrance plane: 0.5 mm,
divergence of pump beam: 125 mrad, incident pump power: 8.5 W

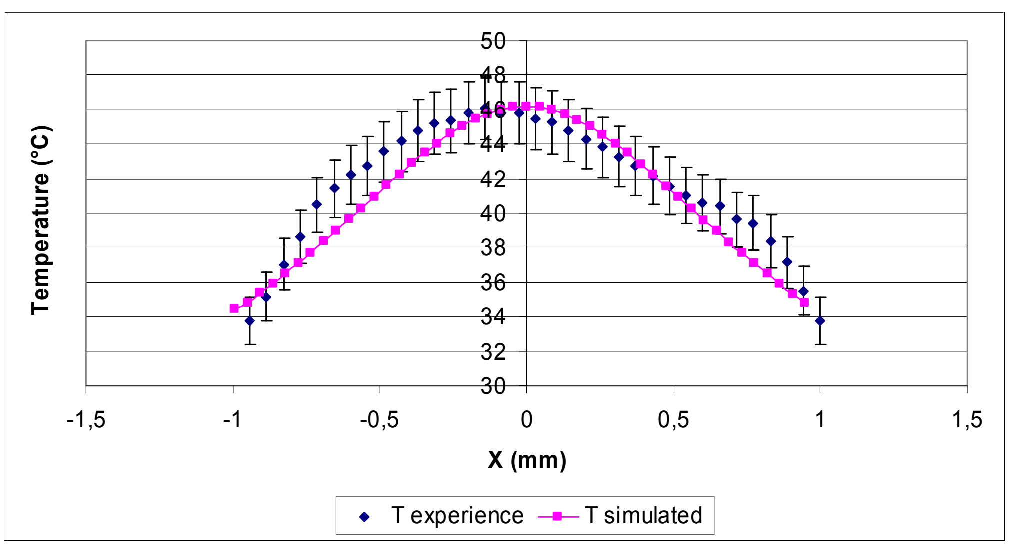

Figure 2. Measured and computed distribution of temperature T for Nd:YAG 1 at. %
at the entrance plane of the pump beam.

The dimensions of the $Nd:YVO_4$ 1 at. % block were: length: 5 mm, width = height: 3 mm.

The pump beam size was reduced to a diameter of 800 µm in order to test the agreement between the simulation and the experiment in another configuration. The incident pump power was 7.5W, the absorption coefficient 8.6 cm^{-1}.

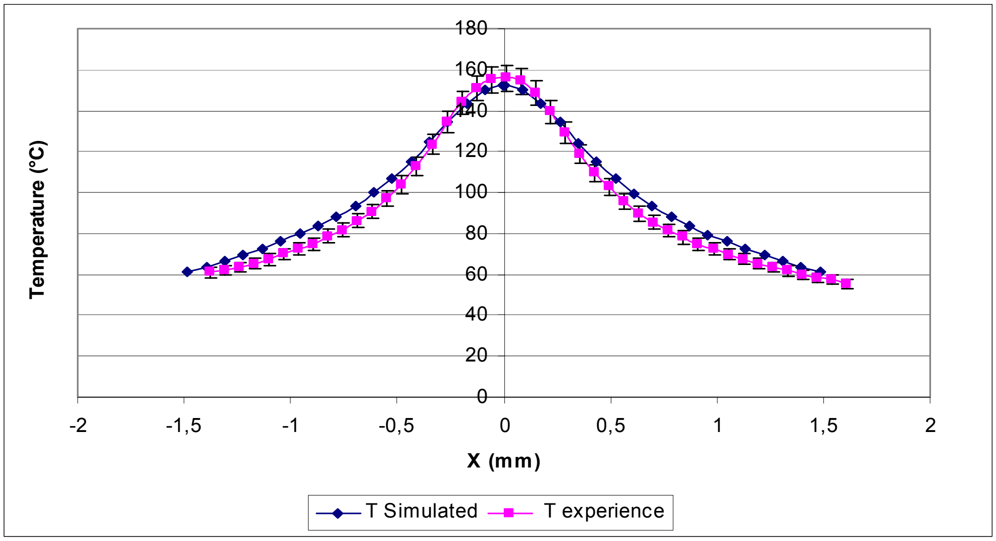

Figure 3. Measured and computed distribution of temperature T for $Nd:YVO_4$ 1 at. % at the entrance plane of the pump beam.

As one can see from Figs. 2 and 3, the agreement between measurement and simulation with LASCAD is very good. Even in the case of a smaller pump spot as used to pump the $Nd:YVO_4$ block, the computed curve is following very closely the measured one. To fit the computed curves to the measured ones a global heat efficiency factor has been used describing the fraction of pump power converted into heat. In case of Nd:YAG, we obtained good agreement for a heat efficiency equal to 0.27 which is close to the commonly reported factor 0.33, see for instance [6]. In case of $Nd:YVO_4$, we used a heat efficiency factor 0.32 which is a bit higher than the factor 0.24 reported by Chen and Kuo [7] for lasing conditions. In this context however, it should be taken into account that laser power extraction reduces the fraction of pump power converted into heat.

5. Conclusions

We have carried through a comparison between high resolution absolute temperature mapping on the surface of diode-end-pumped laser crystals using non-contact infrared measurements and results of Finite Element Analysis (FEA). Our FEA code, which is implemented in the laser simulation program LASCAD [5], uses a semi-unstructured discretization grid that is very well suited for purposes encountered in laser cavity analysis. In two very different cases Nd:YAG (having high thermal conductivity) with large pump spot and Nd:YVO4 (having twice lower conductivity) with smaller pump spot, the agreement between measurement and simulation was very good. Since our measurement technology also allows measuring the temperature distribution during laser power extraction, we will continue our work analyzing thermal effects under lasing conditions.

6. References

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