

Investigation of Thermal Lens Effect of a NdYAG Laser

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ABSTRACT

The resonator of a solid state laser is a very well aligned optical system. As the resonator may be as much as a meter or more in length and precise alignment of the optical elements is required, the whole system needs to be exceptionally stable in order to guarantee reliable function.

On the other hand, the laser crystal is pumped by light from a focused laser diode with significant optical power. This energy is only partly converted into optical energy as the required laser light. Most of the pump energy is lost as heat. The heat is dissipated within the laser crystal and into the mounting system of the crystal. Due to the thermal expansion of material, the crystal and its mounting system are deformed. The deformation of the crystal will cause a so-called thermal lens effect while movement of the mounting system can lead to disalignment of the laser resonator.

In this paper, we describe an experimental set-up to measure the thermal lens effect by means of digital holography. A digital holography microscope was positioned above the laser resonator. The surface of the laser crystal was observed by the microscope via a selectively reflective mirror while the crystal was being pumped and the whole laser system was operating. By changing pump current and laser power, it was possible to monitor both deformation of the crystal surface and deflection of the crystal holder. We present the results of this experiment including an estimate of the stresses and temperatures on the laser crystal induced by its thermal deformation.

KEYWORDS

Digital holography

Laser

Thermal lens

Deformation

Stress

Temperature

1. INTRODUCTION

In principle, a laser consists of an optical resonator formed by two mirrors and an optically active medium. In the case of a NdYAG laser the medium is a NdYAG crystal. The medium is pumped by a high power diode laser with optical energy. Such a resonator of a solid state laser is a very well aligned optical system. As the resonator may be as much as a meter or more in length and precise alignment of the optical elements is required, the whole system needs to be exceptionally stable in order to guarantee reliable functioning.

On the other hand, the laser crystal is pumped by light from a focused laser diode with significant optical power. This energy is only partly converted into optical energy as the required laser light. Most of the pump energy is lost as heat. The heat is dispersed within the laser crystal and into the mounting system of the crystal. Due to the thermal expansion of material, the crystal and its mounting system are deformed, fig. 1. The deformation of the crystal will cause a so-called thermal lens effect while movement of the mounting system can lead to misalignment of the laser resonator. Stresses induced by thermal energy within the laser crystal can even lead to fracturing of the crystal.

In order to quantify these effects, the deformation of the laser crystal was investigated by means of a digital holography microscope. Different effects could be observed including deformation and displacement of the crystal.

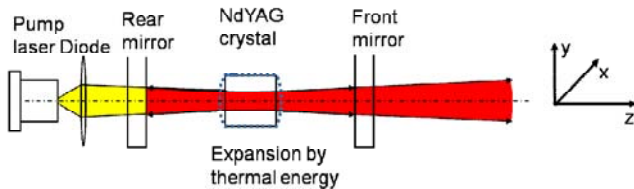


Fig. 1: Principal set-up of a NdYAG laser

2. MEASURING SET-UP

We used a digital holography microscope to measure the thermal expansion effects of the crystal. A digital holography microscope uses the interference of a reference and an object wave to directly record the phase (= shape) of the surface of the measured object.

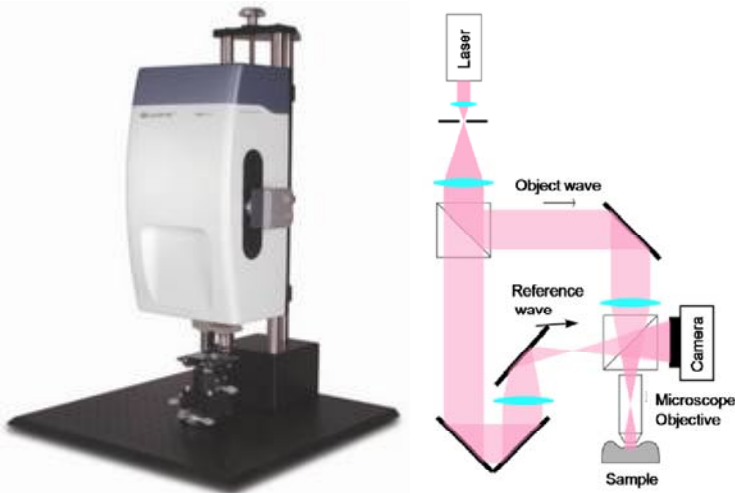


Fig. 2: Digital holography microscope and its optical set-up

In order to separate the wavelengths of the pump laser (981 nm) and the NdYAG laser (1045 nm) from the wavelength of the holography laser (682.5 nm) we used spectral filters. The objective of the holography microscope was positioned vertically above a 45°- filter with 99% transmission for wavelengths above 900 nm and high reflectance for the holography wavelength (682.5 nm). Therefore the laser was still operating. To remove any remaining light in the microscope, an additional narrow band filter was added directly in front of the objective.

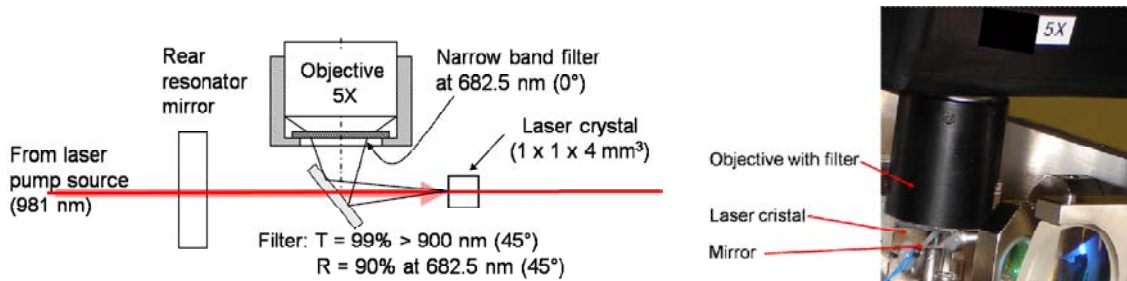


Fig. 3: Introduction of the digital holography microscope into the laser

3. MEASUREMENT RESULTS

3.1 Deformation of the surface

In this configuration measurements were taken at different injection currents of the pump laser. Without pumping, the surface of the laser crystal is nearly flat (fig. 4), while it clearly deforms when the pump current is increased (fig. 5). Additionally, a local defect can be seen in fig. 5. It could be observed that the position of this spot does hardly move if the pump current is changed. This indicates that the lateral position of the crystal remains rather stable.

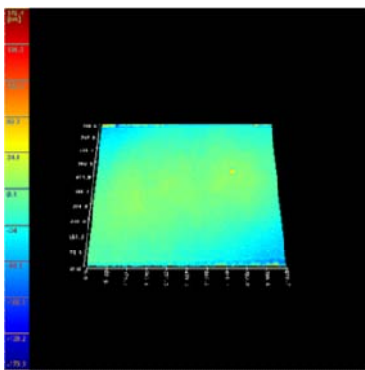


Fig. 4: Crystal surface at 0 A pump current

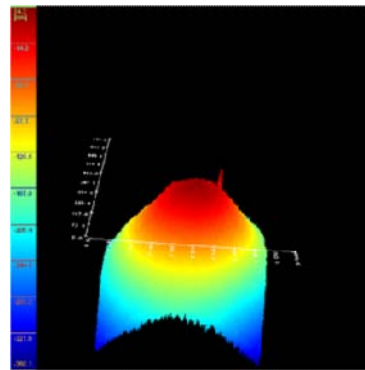


Fig. 5: Crystal surface at 25 A pump current

Fig. 6 shows the profiles of the surface (vertical direction) through the center of maximum deformation. The deflection amplitude increases, as the pump current is increased, but there is hardly any difference between 0 A and 5 A pump current, fig 7. Calculation of the radius of curvature of the thermal lens at the center of deformation leads to fig. 8. The radius of the surface is different in x- and y-direction. It decreases with increasing pump current and reaches nearly 0.5 m at $I_p = 25$ A.

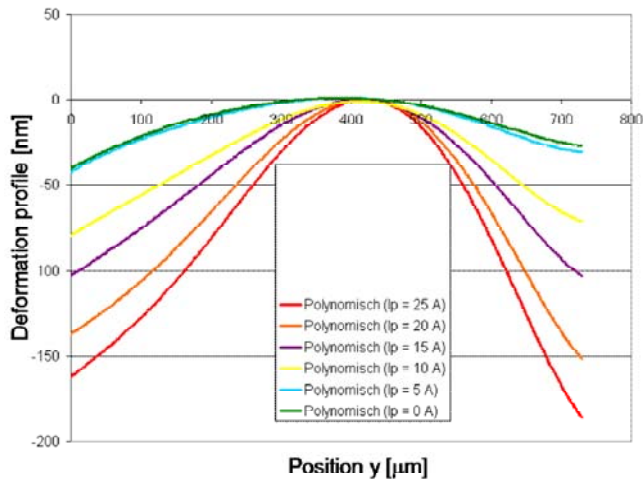


Fig. 6: Deformation profile through the center of the crystal

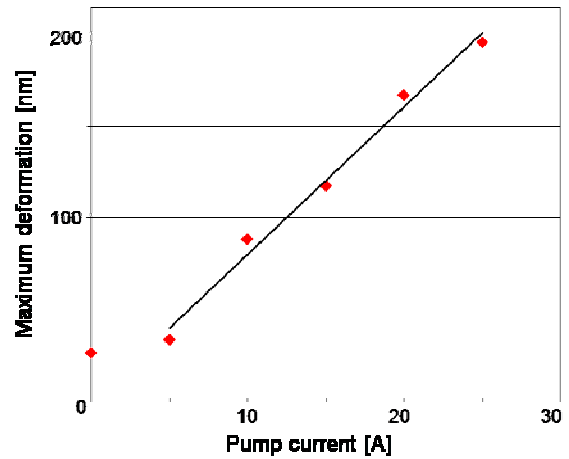


Fig. 7: Deformation amplitude at different pump currents

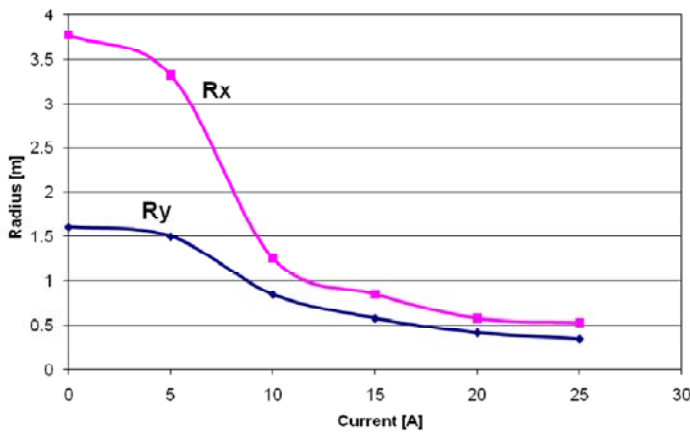


Fig. 8: Radii of curvature in x- and y-direction at different pump currents

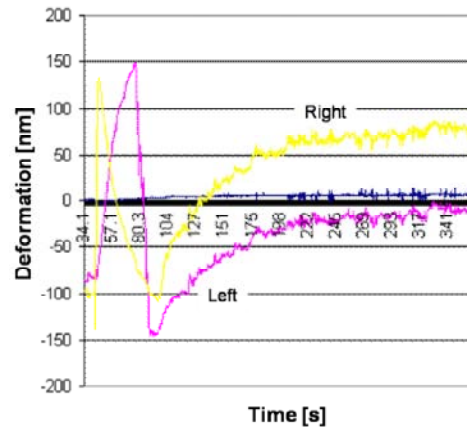


Fig. 9: Transient phenomena

3.2 Transient phenomena

When the power of the laser is changed, transient phenomena are likely to occur. The pump current has been increased in steps of 5 A from 0 A up to 25 A and the deformation was measured with the digital holography microscope. Fig. 9 shows typical behavior of the crystal. The center area of the crystal was defined as zero and the relative displacement of the left and right area was plotted. The graph shows that directly after change in the pump current the crystal moved first on the right side, then on the left side, which means that the complete crystal was deflected. Finally, both areas of the crystal gradually became stable, the left area at zero and the right at 80 nm. This means that, in addition to the deformation, the crystal tilted. The time taken to reach a stable position is ca. 4 - 5 min.

3.3 Lateral movement

As has been mentioned previously, there was a local defect on the crystal (fig. 10). This defect could be used to measure the lateral movement of the thermal lens position when the pump current was changed. In fact, the crystal moves laterally and its amplitude is ca. 15 μm in x and y- direction at maximum pump current, fig.

11. In the presence of a thermal lens effect, lateral displacement can lead to lateral deflection of the laser beam and can therefore cause instability of the laser radiation.

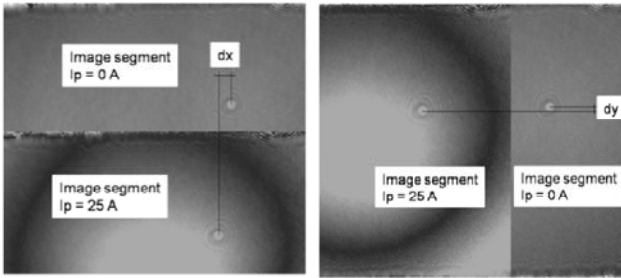


Fig. 10: Lateral movement of the local defect of the crystal

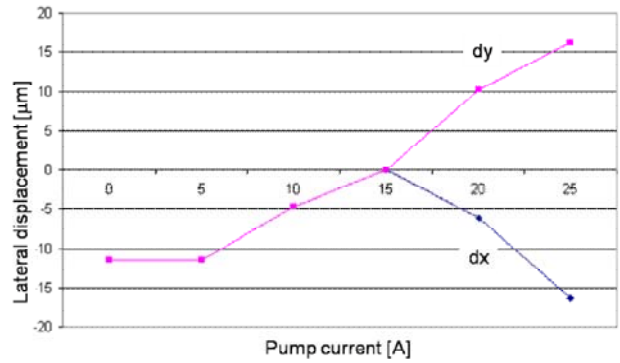


Fig. 11: Lateral displacement of the crystal

4. ANALYSIS

4.1 Crystal temperature

In the non-loaded state (pump current 0 A), the crystal is cooled to 24°C. Therefore, the deformation of the crystal represents the local temperature changes in the crystal. If we assume constant temperature in the direction of the laser beam and symmetric deformation of both optical surfaces of the crystal (fig. 1), we can calculate the temperature distribution with the following formula:

$$T(x, y) = T_0 + \frac{2 \Delta w(x, y)}{l \alpha_g} \quad (1)$$

With $T(x, y)$ = crystal temperature

T_0 = crystal temperature in the non pumped state

l = length of the crystal

α_g = thermal expansion coefficient in z-direction

$\Delta w(x, y)$ = deformation of the crystal surface in z-direction

The result of such calculation leads to the temperature distribution indicated in fig. 12. The maximum temperature reaches 117°C.

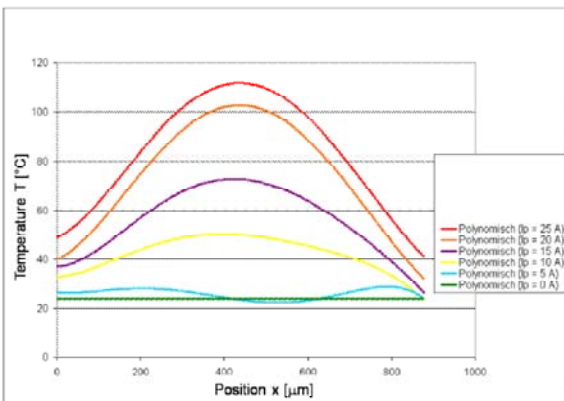


Fig. 12: Temperature distribution in the crystal

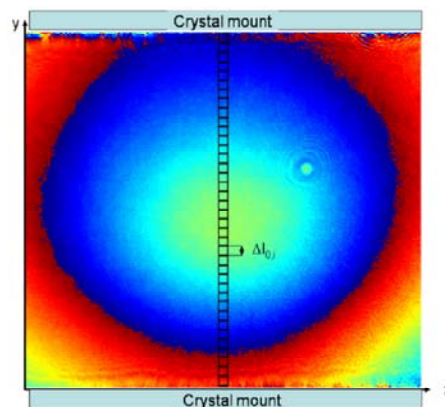


Fig. 13: Calculation of thermal stresses in the crystal

4.2 Mechanical stresses

The crystal is typically mounted in metallic mounts. The thermal expansion coefficients of crystal and mount are different. Therefore, thermal stresses can occur. In a first approach, we can estimate the thermal stresses in the crystal by determining the average temperature change in a cross section and calculating the average elongations in x- and y-direction in the non-stressed state. From these results, we can obtain the stresses if we take into account the flexibility of the crystal mount.

As an example, we can segment the temperature profile in y-direction into many small segments of equal length, fig. 13. The expansion of each segment in y-direction is defined by

$$\Delta l_{y,i} = \Delta l_{y0} \alpha_y \Delta T_i \quad (2)$$

with α_y = thermal expansion coefficient in y-direction (it has to be taken into account that the NdYAG crystal has different thermal expansion coefficients in the different coordinate directions).

Summation leads to the total elongation of the crystal in y-direction:

$$\Delta l_y = \Delta l_{y0} \alpha_y \sum \Delta T_i \quad (3)$$

In this example, the calculation leads to a total expansion of the crystal of 0.2 μm .

If we assume a rigid mount, this thermal expansion would lead to the local stress in y-direction

$$\Delta \sigma_y = E \frac{\Delta l_y}{l_0} \quad (4)$$

with E = Youngs - Modulus of NdYAG = $3.11 \cdot 10^5 \text{ N/mm}^2$

In our case, the maximum stress increase due to thermal loading is ca 60 N/mm^2 . This is a significant amount which must be taken into account in the design of a crystal holder.

5. SUMMARY

The thermal lens effect of a laser crystal has been investigated with digital holography. The instant and full field measuring capability of this technique allows rapid measurement even with transient events. It could be shown that the induced pump energy leads to deformations in the magnitude of some 100 nm, forming a thermal lens of up to 0.5m radius. In combination with a lateral shift of the crystal, the optical stability of the resonator can be significantly influenced.

Additionally, the thermal expansion of the crystal can lead to considerable stresses, which can even lead to crystal fracture.

These measurements help to understand the thermo mechanical behavior of the laser crystal under operation and can lead to improvement of the design of crystal and crystal mount for easier alignment and better stability of the laser resonator.

6. REFERENCES

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