Analysis of Thermal Effect in Thin Disk Laser: A Review

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Abstract. Since its first invitation in 1993, solid-state diode end-pumped thin-disk laser attracts much attention due to its significant improvements in the solid-state laser system. It had many advantages; it has high optical and electrical efficiency, high produced peak power, a simple cooling system, and high beam quality more than the usual solid-state diode laser system. The thin-disk laser (TDL) permits an effective pulse mode, which permits a new type of very short-pulsed laser system that could be used in the industry. Due to the influence of the many factors such as effective cooling system, the type of pumping, and the used thin crystal, a one-dimensional heat flow through thin-disk laser could be achieved which permits excellent enhancement in the beam quality. Finally, in this work, a review is made to the works devoted to discussing the basic principle and the solutions used to analyze the thermal effect in the thin disk laser.

INTRODUCTION

The application of a solid-state laser system finds its way in the industry and laboratories due to its excellent specifications; it has high output power, high efficiency, and good beam quality [1-10]. It was observed that the diode-end-pumped thin solid-state laser occupied intensive attention since its first invitation in 1993 due to its significant improvement in the solid-state laser system. It alone has many advantages such as it has high efficiency, high peak power, a simple cooling geometry, and high beam quality more than that for solid-state diode laser systems [11]. As an example; the beam quality of TDL is better than lasers using a rod as an active medium at the same energy. Uniform pumping reduces the determinate effect of non-uniform temperature distribution in the laser medium. Also, it needs a good cooling system that extracted most of the generated heat produced during laser generation which has a detrimental effect. Also one of the most excellent characteristic specifications of a TDL is its good beam quality, which results from an active cooling system for this type of laser. Fig 1 shows the TDL schematic structure.
The laser medium is chosen to be of disk shape of several mm in diameter and a thickness between 100-200 μm. The backside of the crystal is coated with highly reflective for pumping and the produced laser wavelengths and it is coated with anti-reflective on the other side of the disk for the pumping and the produced laser wavelengths. This disk is mounted with some arrangements to a heat sink where an active nozzle could impose a water jet cooling structure to efficiently extract heat from the disk. A special mounting arrangement could be used to fix the disk with the heat sink to reduce determinately bending of the heat sink and laser medium.

TDL with up to 14 kW now exists as a tool in the industry. The TDL has significantly improved specifications comparing with other types of laser. It has high output power, good efficiency, good beam quality, and efficient pulsed operation [12]. The ability to produce high laser power in TDL attracts high attention from researchers and companies.

LITERATURE REVIEW

Here we review the works that focus on this type of laser and its state of the art:
It was proposed in 1993[11] that the continuous output laser power from a thin disk could be extended to very high output power in the range of kW by increasing the pump-beam radius and/or by using several crystal discs.
K. Contag et al[12], derived an analytical solution to study the effect of different parameters on the efficiency of operation. They used multiple pumping and found that by reducing the thickness, low-temperature results inside the media, and the threshold of lasing reduced, which improves the optical efficiency of the laser medium. In their experimental work, they show that the power of TDL can be extended up to 350 W with good optical efficiency as the number of passes increased.
J. Mende et al [13] studied a thin-disk laser of Yb:YAG crystal as a function of pumping power in different resonators. They noticed a small thermal lens because of the geometry of the thin disk. It was found also that there was a strong dependency on the pump power density on the laser mode. They confirmed their result experimentally. The results opened the possibility of scaling the fundamental mode power into the multi-kW-regime.
J. Mende et al [14] showed that by using dynamically stable resonators, the thermal lens effect could be significantly reduced. They found that using one disk, an output power of 500 W with an averaged M² = 1.55 could be reached, and the output power could be doubled by using two disks.
J. Mende et al [15] studied dynamically stable resonators in a thin-disk laser to minimize thermal lens. A one disk resonator with an output power of 0.5 kW was achieved and the output power is doubled as they used a 2 disk-resonator with an acceptable optical efficiency in fundamental mode operation.
Speiser et al [16] combined the numerical model and FEM software in studying the ability to extend the power in thin Yb:YAG disk laser, particularly they studied stress, thermal lensing, and disk mounting. Depending on the obtained result it was shown that 14 kW laser output power is possible with small thermal lensing. This analysis can be easily extended to higher pump power and subsequently higher output power.
J. Shang et al [17] derived an exact solution to determine the effect of thermal lensing in an end-pumped TDL assuming that in solid-state laser (especially in TDL), thermal lensing reduces the output beam quality and optical efficiency. In their work, they calculated the temperature distributions, stress, strain, and expansion in the disk. They proposed an expression for the thermal lens focal length as a function of its diameter. From the result, one can conclude that the aspect ratio and the laser mode of the gain region can be modified to minimize their effects on thermal lensing.

H. Yang et al [18] used FEM to study the thermal effects (i.e. stress, strain, birefringence, and thermal lensing) in Nd:YAG TDL. One of their findings was that the fringing region of disk crystal was the first part that fractured while exposed to excessive pumping power.

G. Zhu et al [19] derived a detailed and exact plane wave model with non-uniform temperature distribution in the thin-disk medium for multiple pass pump conditions with various resonator shapes in a Yb: YAG disk laser. The rate equations and the axis-symmetry heat equation were used by an iterative solution to determine the temperature distribution in the medium. Depending on the obtained analytical solution, the density of laser-output power, threshold power density, slope efficiency, and dopant concentration on different parameters were determined. It was found that the obtained solution is more accurate than the model that was not considering the non-uniform temperature effects.

G. Zhu et al [20, 21] derived an analytical solution for temperature distribution in TDL, and combined the analytical method with FEM software to obtain the OPD in a TDL. They obtained the temperature distribution and its effects (OPD, axial strain (bulging), and thermal strain-induced birefringence and deformation). They analyze the OPD in end-pumped TDL assuming that it has two main parts: the spherical and aspherical parts, where the latter seems to be the main cause that affects beam quality.

G. Zhu et al [22] also derived a model for an end-pumped TDL that uses the rate equation with the variation of fractional thermal load, under lasing and non-lasing situations. An iterative method was used to calculate the temperature and fractional thermal load in a thin laser medium for different radiative quantum efficiencies. The obtained results were found to be more accurate than the models that did not consider the variation of fractional thermal load.

Z. Ye et al [23] measured the convective heat transfer coefficient due to the direct cooling of Nd:YAG thin laser slab at different mass flow rates of cooling fluid. Using these coefficients in a numerical solution, the temperature and thermal stress in the laser medium were obtained. It was found that as the heat transfer coefficient increased, the maximum allowable thermal load could be increased too. Their result has a significant impact on a designer to suitably choosing working parameters in a high-power thin-disk laser.

T. Dietrich et al [24] used FEM to study the effect of natural cooling on thermal distortion in a laser beam. It was found that the decrease in pump spot radius strongly increased the angular tilt and at the same time increased the dioptric power of the spherical contribution. These developed facts seem to be very effective in designing high-power thin-disk laser.

K. S. Shibib et al [25] solved the heat equation that modeled a thin-disk laser disk using an integral transform method. They obtained the temperature distribution, stress, strain, and OPD. They neglected the deformation of the heat sink where the thin disk is soldered and they assumed that the deformation resistance is high enough so that the heat sink can be regarded as an ideal rigid body where the crystal bending due to deformation of the heat sink can be ignored which simplify the solution of obtaining OPD. It was found that reducing disk thickness, and increasing the heat transfer coefficient seems to seriously reduce temperature distribution, stress, strain, and OPD in the pumped region.

CONCLUSIONS

By using a solid-state TDL, the possible output power could be extended due to its excellent properties where an efficient cooling system is used to extract the part of the pumping power which is already converted to heat. Using YP: YAG crystal can reduce the generated heat also because of its quasi-three-level nature it requires an efficient cooling system. TDL also has higher electrical efficiency than another type of solid-state laser system. The main concept behind using the TDL is its possible large surface-to-volume ratio which provides excellent cooling ability to ensure approximately one-dimension heat flow through a thin disk which results in very good beam quality. In this work, we explored the works that are devoted to this type of laser and it seems that huge
advantages could be gained by using this type of laser. One of the most promising advantages is that the output power could be extended to huge ranges so as it can be used in industry and military applications that required high laser power.

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