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The influences of amplified spontaneous emission, crystal temperature and round-trip loss on scaling of CW thin-disk laser

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A B S T R A C T

In this paper, a model is built to explore how the parameters (amplified spontaneous emission (ASE), temperature and round-trip loss) influence the output power in a thin-disk laser. It is found that optical efficiency of the disk laser is reduced with the increase of ASE, temperature or round-trip loss. The parameters are optimized to maximize the output power based on our model. We find that it is necessary to balance the need to lower the temperature with the need to control ASE during the optimization process. But the balance becomes more difficult to achieve with the increase of round-trip loss. We conclude that output power of more than 2.6 MW with a single disk can be achieved, but the necessary disk size (more than 0.5 m) is far beyond the actual technical limits. But it is possible to achieve output power of over a hundred kilowatts using a 10 cm disk in the near future.

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1. Introduction

In the past decade the technologies of thin-disk laser have been developed rapidly [1–9]. A laser output of high power, high efficiency and good beam quality can be achieved simultaneously using an Yb:YAG thin-disk laser with diode laser array pumping [10]. The output power of 5.5 kW and more than 60% optical efficiency with a single thin-disk laser in continuous-wave were reported [11]; the laser system of up to 8 kW output power using 4 disks is commercially used for materials processing [9]. In [12] Speiser and Giesen present some numerical results suggesting that an output power of more than 14 kW with one disk is possible. Using a Monte Carlo tracing of ASE photons through the thin disk crystal, a laser power of about 40 kW and 40% optical efficiency is possible with a 0.2 mm thickness Yb:YAG disk mounted on a heat sink and using a high reflective (HR) coating design that absorbs most of the ASE [13]. The amplification, absorption and transmission of ASE photons were observed, but this result was not the scaling limits of thin-disk laser.

The scaling limits of thin-disk lasers have already been considered. Kouznetsov et al. point out that surface loss is a key factor limiting the maximum achievable power [14]. They assume the spontaneous emission amplified length to be L, which is the transverse size of the pumping spot. With the same estimate of amplified spontaneous emission (ASE) intensity, a disk with an anti-ASE cap was reported [15–17], and the effective lifetime significantly increased relative to the disk without an anti-ASR cap. Nevertheless, in the above researches, the amplified length of ASE photon was not accurately considered. But a different viewpoint was presented [18]: Paschotta et al. estimate that the spontaneous emission amplified length in [14] is not reasonable and consider that the estimation of round-trip loss in [14] is rather pessimistic. A different approach of calculating the spontaneous emission amplified length using geometric methods was presented in [13]. The ASE photon flux density on a specific point in disk was analytically solved, and the maximum achievable power of 35.9 MW with a single disk was calculated. But the ASE photons flux density cannot be obtained for all points of the gain volume. Therefore, an estimated value of average ASE intensity, much greater than the actual value, was used. And in this scaling model, it is unrealistic to assume that temperature remains constant.

In this paper, a model of the relationship between the output power and the key factors of scaling (ASE, temperature and loss) is built to estimate the scaling limit of thin-disk laser. In this model, the number of multi-pumping passes is also considered. In Section 2, we calculate two-dimensional space distribution of ASE photon flux density in the gain region and the effective upper level lifetime without considering the axial-component. The relationship between the effective upper level lifetime and the parameters of laser operation such as pumping power, size of gain region, *etc* are explored. In Section 3, the temperature of the disk crystal and the round-trip loss are introduced. In Section 4, we present a model to calculate the output power based on a quasi three-level system.

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In Section 5, the maximum output power with a single disk is calculated, and the elements limiting the output power are analyzed.

2. Amplified spontaneous emission

ASE of disk laser deserves extra attention because the radial dimension of the gain region is much greater than the thickness of disk crystal. Some spontaneous emission photons can move a long trip in the gain volume and be amplified on the path. With the increase of gain coefficient or transverse size, more excited ions transition to ground state as amplified spontaneous emission, and effective lifetime is reduced as a result.

To calculate the effective lifetime at one point in the gain volume as determined by ASE, we have to calculate the ASE photon flux density reaching this point from each point of the disk. In [13] the analytic expression of ASE photon flux at points on the axis of the disk is obtained using some approximate conditions in spherical coordinate system. This result is exact and succinct. Unfortunately, under their approximate conditions, ASE photon flux at other points cannot be obtained without losing the rotational symmetry.

2.1. A model of calculate ASE intensity in a disk crystal pumped by a rectangular spot

We consider a disk with thickness h, and the uniform pumping spot is a square with size $2X$ by $2Y$. The gain and excitation density is homogeneous, and the gain volume is radially surrounded by highly absorbing material. In this paper, the shape of the pumping spot is rectangle, which is different from circular pumping spot in general disk laser [1,13]. This rectangular pumping spot can be achieved in our experimental scheme using a novel multi-pumping system, in which our disk laser operates in kilowatt order far smaller than the power scaling limit. In common pumping system, because the beam qualities of LD array are different between fast axis and slow axis, the beam outputted from LD array must be coupled into fiber bundle or homogenization rod in order to shape the LD beam into a circular spot. Then the spot are imaged on disk by collimation lens and paraboloidal mirror. The shaping system is complex, and the temperature of fiber bundle or homogenization rod is very high when the operating power is high. In our system, the pumping spot is the image of bars on slow axis and the spatial frequency of beam on fast axis. And the image of bars and spatial frequency are homogenized by specific design of cylindrical lens group. This collimation and homogenization scheme is simple and feasible since it is not necessary to focus or propagate beam with small cross section. High temperature is not observed in this system. The cross section of beam on paraboloidal mirror is rectangular with a high length–width ratio. The pumping beam is focused on disk crystal 11 passes uniformly by our multi-pumping system without complex folding mirror. The collimated beams on the paraboloidal mirror are displaced on direction of fast axis in reimaging. The distribution of multi-pumping intensity on the disk is shown in Fig. 1, where the size of spot on disk is 8.5 mm by 8.5 mm. In this paper, our pumping scheme will not be discusses in detail. In high power operation, the temperature rise of disk crystal depends on the thickness of disk and the pumping intensity, but does not depend on the shape of the pumping spot. Laser will be operated in multimode to achieve higher output power so that the laser modes can match with gain region in both rectangular pumping and circular pumping. With equal pumping area, the ASE in the corner of rectangular spot is stronger than that in the edge of circular spot. But the average effective lifetime is similar under both pumping conditions because the side length of rectangular spot is smaller than the diameter of circular spot. Overall speaking, the advantage of pumping with a rectangular spot is that the collimated and homogenization design is simpler and the device can accommodate higher pumping power. But the disadvantage is the effective lifetime distribution is less uniform because of strong ASE in the corner region. And the diameter of disk with rectangular pumping is larger than that with circular pumping under same pumping area. These effects will be discussed in detail in Sections 3 and 4.

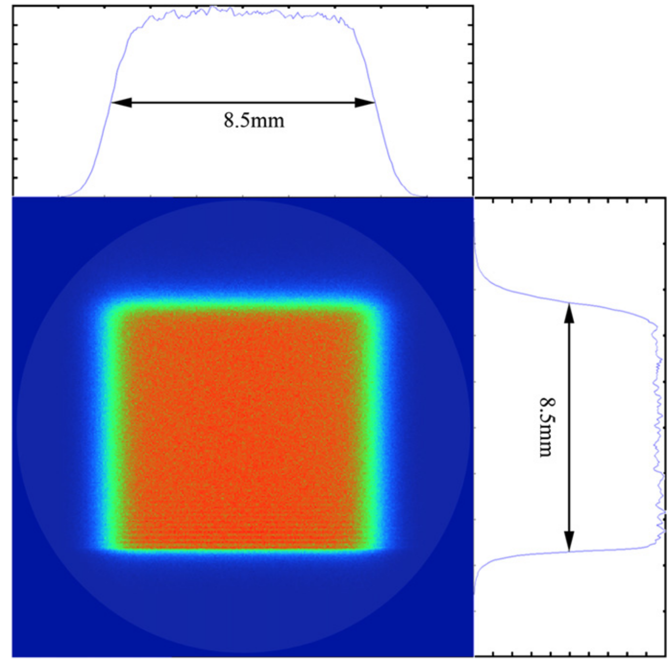

Fig. 1. The distribution of multi-pumping intensity on the disk. The size of pumping spot is 8.5 mm by 8.5 mm.

The HR coating on the end surface of the disk, which works as the mirror of resonant cavity, reflects at laser wavelength λ_L and pumping wavelength λ_P when the angle between the incidence and the normal of the surface is small. And the other surface is antireflective (AR). It is possible to reduce the acceptable angle of HR coating and increase the acceptable angle of AR coating at laser wavelength to avoid repeated ASE reflection between the two surfaces. To simplify the calculation, we assume the ASE will be reflected at the HR surface only if $\phi < \alpha_0$ and at the AR surface only if $\phi > \alpha_0$, so no light can be reflected at the two surfaces alternately and repeatedly. An ASE photon can reach a point O via three possible paths as sketched in Fig. 2(a): from A to O directly without reflection; from B to O being reflected at HR surface; from C to O being reflected at AR surface. So there are two ways for an ASE photon to move from one point to another in the gain volume: to move directly or to be reflected only once.

Negligible thermal lens effect is an important advantage of thin-disk laser, and Yb:YAG as quasi three-level laser material is sensitive to temperature. In end cooling design, the disk cannot be too thick in high power operation. These characters will be discussed further in Section 3. So $2X \geqslant h_{disk}$. The maximum value of axial movement component from one point to another is $2h_{disk}$ because of the number of reflection at surface is at most 1. Moreover, amplification on long path is the primary cause of the increase of ASE photons flux density. So the axial component could be ignored in ASE photons trace in the gain volume.

In order to calculate ASE and effective upper level lifetime at (x_0,y_0) in the gain region with an area of $2X \times 2Y$ and uniform gain coefficient g, we have to compute the ASE photons flux density $\Phi(x_0,y_0)$ first. We will get a density of spontaneous emission photons n_2/τ in this gain region with homogeneously excited ions n_2 and upper level lifetime τ. A volume element at (x,y) of size

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