

Research Article

Fluorescence Radiation and Thermal Effect at the Edge of the Disk-Shaped Laser Crystal

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The fluorescence radiation property at the edge of the thin disk crystal is very important to the design of thin disk lasers. In order to study this effect, in this paper, we established a theoretical model to describe the edge fluorescence radiation process in thin disk lasers. Subsequently, we used a thin disk crystal with indium absorption cladding to quantitatively test the edge fluorescence intensity. The significant difference between measured and simulated data can be described as P (probability value) < 0.1 at the edge when the measured temperature is lower than the melting point of the metal cladding, and P < 0.05 at the pump area. Finally, we analyze the influence of the edge fluorescence radiation on the thin disk laser operation, and the results show that the edge thermal effect will reduce the conversion efficiency of the disk lasers. The research can provide theoretical guidance for the designing and packaging process of crystal elements in thin disk lasers.

1. Introduction

A thin disk laser can promise its high average power, high peak power, and high beam quality by using the thin disk shaped laser crystal [1], which is widely used in laser drilling [2, 3], cutting [4], and welding [5], etc. At present, the main factor limiting the output characteristics of thin disk lasers is the transversely transmitted fluorescence photons, especially edge-radiated fluorescence photons [6]. When the gain in the pump area increases, the edge-radiated fluorescence photons are converted into spontaneous emission photons [6] or even into parasitic oscillation photons [7], which consume a large excited population and greatly reduce the conversion efficiency of thin disk lasers. Therefore, to improve the output characteristics, it is important to investigate the edge-radiated fluorescence of thin disk lasers.

In order to investigate the edge-radiated fluorescence of thin disk lasers, researchers carried out a lot of work. In 1986, Lowenthal and Eggleston first theoretically analyzed the transverse fluorescence photon flux density in thin disk lasers. The model included multiple reflections of fluorescence on the upper and lower surfaces, narrowing of the fluorescence line width, and the effect of unsaturated absorption of thin disk crystals on edge-radiated fluorescence [8]. Due to the randomness of spontaneous emission fluorescence and the coupling between gain distribution, temperature distribution, and fluorescence flux distribution, the calculation process is very complicated. In order to simplify the model, the researchers used many methods to theoretically analyze the transmission process and fluorescence characteristics of edge-radiated fluorescence in disk lasers, such as the analytical method [9], semianalytical method [10], finite element analysis method [11], Monte Carlo method [12]. However, since the radiation range of edge-radiated fluorescence covers the entire solid angle of 2π (hemisphere region) [13], it is difficult to measure it directly by conventional methods, and the current research on edge-radiated fluorescence in disk lasers is still at the stage of theoretical analysis. Therefore, it is necessary to measure the edge-radiated fluorescence of thin disk lasers quantitatively.

On the other hand, as shown in Figure 1(a), the fluorescence of the thin disk crystal is mainly distributed in the pump region and the edge side. Therefore, the heat generates not only in the pumped area but also in the unpumped area and edge of the thin disk. According to Figures 1(b) and 1(c), not only the dielectric coat on the crystal-air surface is damaged but also the crystal is directly burned too. In order to solve this problem, in 2012, Su and Eggleston investigated the transmission process of fluorescence and amplified spontaneous emission (ASE) photons in the thin disk crystal by using the ray-tracing method and studied the spatial distribution of the fluorescence in the thin disk crystal at different edge conditions [12]. Moreover, to verify the fluorescence intensity at different positions of the thin disk crystal, in 2019, Chen et al. established a theoretical analysis of the fluorescence spectra in different areas of the thin disk and measured the spectra of the fluorescence emitted from the pump area and the side of the thin disk crystal through experiments [13].

Based on Chen's theory [13], in this paper, we studied the transverse transmission of fluorescent photons in the nonpumped area of the thin disk crystal both in simulation and experiment. And then, based on this model, we studied the thermal effect induced by the edge-emitting photon. The edge fluorescence radiation intensity model based on the reabsorption of the nonpumped region is established, and the thermodynamic simulation based on finite element analysis is performed on it. At the same time, the theoretical model and the simulation results are verified by the experiment.

2. Theoretical Analysis and Numerical Simulation

2.1. The Theoretical Model of the Edge Fluorescence Radiation Intensity. In this section, the theoretical and numerical model of the edge fluorescence radiation of the thin disk laser is to be established. A pump-probe model [13, 15] was used to establish the physical model of the edge fluorescence radiation. In this model, the total fluorescence radiation power radiated to the edge of the pump area of the disk laser can be described as follows:

$$P_f = P_{\text{pump}} \cdot \eta_q, \tag{1}$$

where, P_{pump} is the absorbed pumping power, and η_q is the laser quantum efficiency, which can be calculated as follows:

$$\eta_q = \frac{\lambda_p}{\overline{\lambda_f}},\tag{2}$$

where, λ_f is the average fluorescence wavelength which can be calculated as follows:

$$\overline{\lambda}_f = \frac{\sum \lambda \cdot \Phi_f(\lambda) \delta \lambda}{\sum \Phi_f(\lambda) \delta \lambda},\tag{3}$$

where, Φ_f is the fluorescence flux and $\delta\lambda$ is the step of Φ_f . Actually, most of the photons propagating in the crystal are ASE photons. But according to Lin et al. [16], there is no obvious difference between the average wavelengths of ASE and fluorescence photons when the pumping density < 6 kW/cm^2 or the pumping diameter <20 mm. Therefore, in general, we can use the average fluorescence wavelength instead of the average ASE wavelength. When the fluorescence is radiated into the unpumped area, the fluorescence photons will be reabsorbed, especially for the quasi-threelevel crystal such as Yb doped crystal. According to Chen et al. [13], nearly all of the fluorescence power was radiated from the edge side. Therefore, the total power radiated to the edge of the thin disk crystal can be described as follows:

$$P_{\text{edge}} = P_{\text{pump}} \cdot \eta_q \cdot \exp\left(-\overline{\alpha}_0 \cdot \overline{S}_{\text{Reabs}}\right),\tag{4}$$

where, $\overline{\alpha}_0$ is the average small signal absorption coefficient of the fluorescence photons in the unpumped area, which can be calculated as follows:

$$\overline{\alpha}_{0} = -\ln \frac{\left[\sum_{\lambda} I_{f}(\lambda, 0) \exp\left(-\alpha^{0}(\lambda) \cdot \overline{S}_{\text{Reabs}}\right) / \sum_{\lambda} I_{f}(\lambda, 0)\right]}{\overline{S}_{\text{Reabs}}}, \quad (5)$$

where, I_f is the intensity of fluorescence radiation

$$I_f(\lambda) = \Phi_f(\lambda) \cdot h\nu, \tag{6}$$

where, hv is the energy of the fluorescence photon. α^0 (λ) is the small signal absorption coefficient of the fluorescence photon. Mention that, as shown in Figure 1(a), since the central fluorescence radiation region is limited to the pump region, it can be considered that the fluorescence radiation in the nonpump region absorbs the pump light very weakly, so we can assume that the reabsorption effect in the nonpump region can be approximated by this small signal absorption.

 S_{Reabs} is the effective re-absorption length, as shown in Figure 2. Due to the total internal reflection, the reabsorption length of the multiple reflections of fluorescence inside the thin disk crystal can be simply solved by the mirror image method (as the mirror region in Figure 2). In Figure 2, R_{pump} is the radius of the pump area, R_{disk} is the radius of the thin disk crystal, and α_c is the critical angle of total internal reflection. According to Figure 2, the average reabsorption length can be described as follows:

$$\overline{S}_{\text{Reabs}} = \frac{\int_{\alpha_c}^{\pi/2} (R_{\text{disk}} - R_{\text{pump}}/\sin\theta) d\theta}{(\pi/2) - \alpha_c}.$$
 (7)

In order to quantitatively measure the edge fluorescence radiation intensity, the method of metal absorption cladding is proposed in this paper. By measuring the temperature rise



FIGURE 1: (a) The photograph of the pumped thin disk crystal [13]. (b) The photograph and (c) metallograph of the edge burned Yb: YAG thin disk crystal [14], which were produced by Huazhong university of science and technology.

after the metal absorbs the fluorescence, the fluorescent intensity radiated from the edge side can be quantitatively evaluated.

As shown in Figure 3, the absorbed cladding consists of metal cladding on the edge of the thin disk. Here, the absorbed fluorescence intensity by the absorbed cladding on the side can be calculated as follows:

$$I_{\text{edge}} = P_{\text{pump}} \cdot \eta_q \cdot \exp\left(-\overline{\alpha}_0 \cdot \overline{S}_{\text{Reabs}}\right) \cdot \left(1 - R_{\text{cladding}}\right) \cdot \eta_{\text{cladding_edge}} \cdot A_{\text{side}}^{-1},\tag{8}$$

where, R_{cladding} is the reflectivity of the metal cladding, $\eta_{\text{cladding}_edge}$ is the area ratio of the cladding to the side surface, and A_{side} is the area of the thin disk edge side. According to Equation (8), the thermal effect on the side of the thin disk crystal caused by the fluorescence can be analyzed. In the next section, the edge radiation and thermal effect will be simulated in Yb:YAG thin disk laser by the previous model.

2.2. The Theoretical Analyze and Numerical Simulation of the Edge Radiation and Thermal Effect of the Yb: YAG Thin Disk Laser. The conversion efficiency of Yb: YAG disk laser based on a quasi-three-level structure is very sensitive to temperature, therefore it is very important to study the edge thermal effects. Figure 4 shows the energy level diagram of Yb: YAG consisting of an upper manifold [13] ${}^{2}F_{5/2}$ and a lower manifold ${}^{2}F_{7/2}$. f_{1i} , E_{1i} and f_{0j} and E_{0j} are the Boltzmann occupation factors and wavenumbers for each Stark level of the upper and lower manifold, respectively. N_{2} and N_{1} are the populations of Yb³⁺. A_{i} and Z_{j} are the Stark energy levels.

The Boltzmann occupation factors can be written as follows:

$$f_{1i} = \frac{\exp(-hcE_{1i}/kT)}{\sum_{p=1}^{3}\exp(-hcE_{1p}/kT)}, f_{0j} = \frac{\exp(-hcE_{0j}/kT)}{\sum_{p=1}^{4}\exp(-hcE_{0p}/kT)},$$
(9)

where, h is the Plank constant, c is the light speed in the vacuum, k is the Boltzmann constant, and T is the temperature. Considering the spectral broadening, the normalized lineshape function can be described as the following:

$$\begin{cases} g_{s}(\nu) = \frac{g_{s}'(\nu)}{\sum[g_{s}'(\nu)\delta\nu]}, \\ g_{s}'(\nu) = \sum_{i=1}^{3}\sum_{j=1}^{4}f_{1i}\frac{\beta_{0j}^{1i}}{\sum_{j=1}^{4}\beta_{0j}^{1i}}L(\nu,\nu_{ij}), \end{cases}$$
(10)

where, β_{0j}^{1i} is the fluorescence branch ratio of Yb : YAG from level A_i to Z_j . $L(v, v_{ij})$ is the Lorentz lineshape function

$$L(\nu, \nu_{ij}) = \frac{\Delta \nu/2\pi}{\left(\nu - \nu_{ij}\right)^2 + \left(\Delta \nu/2\right)^2}.$$
 (11)

Then, the fluorescence flux can be calculated as follows:

$$\Phi_f(\nu) = \frac{N_2 dV}{4\pi r^2 \tau_0} g_s(\nu) \delta\nu, \qquad (12)$$

where, τ_0 is the fluorescence lifetime of the manifold ${}^2F_{5/2}$, r is the distance between the receiver and emitter position of the fluorescence, dV is the volume element around the emitter position, and δv is the frequency step. According to Equations (1)–(11), the temperature at the edge side of the thin disk crystal can be simulated by using the finite element analysis method with the help of COMSOL. It has to be mentioned that when there is no laser output, the parameter $\overline{\lambda}_f$ is calculated by iteration of the central temperature of the thin disk crystal (obtained by the finite element method). In the next section, this model will be tested by the experiment.

3. Experiments and Discussions

3.1. Experimental Study on the Heat Generation of the Fluorescence Radiation at the Edge of the Thin Disk Crystal. In order to demonstrate the theoretical model and simulation



FIGURE 2: Mirror diagram of fluorescence transmission path in thin disk crystal.



FIGURE 3: The scheme of the thin disk crystal with or without AC.

above, indium soldered Yb:YAG thin disk mounted in a multipass pump module was used in the experiment which was made by Huazhong University of Science and Technology. The diameter of the thin disk crystal was 10 mm, the thickness was ~250 μ m, and the doping concentration was 10 at (%). The material of metal absorption cladding is indium. In order to measure the fluorescence radiation intensity on the edge of the thin disk crystal, an experimental setup based on a multipass pumping structure was established as shown in Figure 5.

In the experiment, a 24-time pumping scheme was used to improve the absorption efficiency of the thin disk crystal [17]. A fiber-coupled 940 nm diode laser was used as a pump source with a maximum power of 1000 W, of which the fiber core is square in cross-section. The pumping spot on the thin disk crystal was a square sized $4 \text{ mm} \times 4 \text{ mm}$. The edge and the pumping area temperature of the thin disk crystal were measured by an infrared thermal imager (Testo 890-2). Figure 6(a) shows the thermal imager, based on the thermal image, the central and edge temperature of the thin disk crystal can be processed by the software of IRSoft (Testo's own image processing software), which are shown in Figure 6(b).

Numerical simulations were used to verify the theory of edge radiation and thermal effects according to the experimental results. Assuming that 95% of the pump energy is absorbed by the multipass pumping scheme, we simulated the thermal effect of the thin disk crystal according to the previous theory. The parameters used in the simulation are shown in Table 1.

Figures 7(a) and 7(b) are the simulated and measured temperatures at the central and edge of the thin disk crystal without laser output, respectively. Mention that, actually we have carried out 6 sets of experimental measurements for each temperature to reduce its random error, but because the

root mean square (RMS) is too small (except when the pump power is 50 W RMS~ 3.2° C, the RMS under the other pump power is less than 0.1° C), so Figures 7(a) and 7(b) show only average measurements.

Obviously, the measured central temperatures matched the simulated ones well. As for that at the edge, the numerical simulation and experimental results match well under the temperature of ~150°C; while when it exceeds ~150°C, the measured data increase more rapidly than the simulated results. Considering that the melting point of indium is 156°C, it is believed that the cause of the nonlinear temperature rise is that the temperature of the edge exceeds the melting point of the cladding, which leads to an increase in the absorption coefficient of the fluorescence, resulting in temperature rise. The significant difference between measured and simulated data can be described as P (probability value) < 0.1 at the edge when the measured temperature is lower than the melting point of the metal cladding, and P < 0.05 at the pump area. Obviously, the experimental data and the model prediction are matched very well; this shows that the physical model in this paper can effectively and quantitatively evaluate the edge fluorescence radiation intensity.

Next, we will analyze the influence of cladding on the thin disk laser by comparing the temperature and laser conversion efficiency of the thin disk crystal with or without cladding.

3.2. Influence of the Edge Heat Generation on the Thin Disk Laser Operation. In order to investigate the influence of edge heat generation on the thin disk laser operation, a chamfering operation was adopted to the thin disk edge for the same thin disk crystal. The metallographic diagram of the chamfered edge is shown in Figure 8.

There is no obvious roughened surface between the edge (bottom surface) and the heat sink in Figure 8. The average depth of the chamfer is about 900 μ m, corresponding to an angle of about 15 degrees. It can also be seen that the chamfer brings a little damage to the coating of the upper surface. After the edge was chamfered, the temperatures of the thin disk crystal operated with and without laser output were measured. The results are shown in Figures 9 and 10.

Figures 9(a) and 9(b) show the variety of the edge temperatures with the pump power with and without indium cladding it when without and with laser operation, respectively. The temperatures drop significantly in both without indium cladding. Figures 10(a) and 10(b) show the variety of the central temperatures with the pump power with and without indium cladding with and without laser operation, respectively. Compared with the edge temperatures, the center temperatures before chamfering are just slightly higher than the ones after chamfering. It is supposed that the slight temperature difference before and after chamfering is due to the heat transfer from the edge to the center. To verify this assumption, the part of central temperatures caused by the heat transfer was calculated, and the results are shown in Figure 11.



FIGURE 4: Yb: YAG energy level diagram at 300 K [13].



FIGURE 5: The experimental setup for measuring the temperature of the thin disk laser.



FIGURE 6: (a) The thermal image of the thin disk crystal taken by the infrared thermal imager. (b) The measured temperature from the edge and central of the thin disk crystal.

Figure 11 shows that the simulated center temperature rise caused by the heat transfer under the 250 W pump is about 2°C, while the measured one is about 6°C, between which the difference is not significant. The difference between the experiment and the simulation may be caused by the discrepancy between parameters used in the experiment and the numerical simulation, such as the thermal conductivity and thermal resistance of the crystal.

Finally, the optical to the optical (opt.-opt.) conversion efficiency of the thin disk crystal with and without indium

cladding was measured. A V-shaped resonator was used in the experiment. The diameter of the end mirror is 25.4 mm, with a radius of curvature of -1 m, HR coated at 1030 nm. The length from the end mirror to the thin disk is 0.35 m. The output mirror is flat with a diameter of 25.4 mm and a transmittance of 10%. The length from the output mirror to the thin disk is 0.48 m. The results are shown in Figure 12.

The threshold of the pump power reduced without cladding, meanwhile the slope efficiency and opt.-opt. conversion efficiency increased. When the thin disk edge was

TABLE 1:	The	parameters	used	in	simulation.
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Parameters	Value
Pumping wavelength (λ_p)	940 nm
Average fluorescence wavelength $(\overline{\lambda_f})$	1005 nm
Average absorption length $(\overline{S_{\text{Reabs}}})$	3.685 mm
Reflectivity of solder $(R_{I_{\rm eff}})$	0.785
Cooling convective heat transfer coefficient	$4 \times 10^4 \mathrm{W/(cm^2 \cdot K)}$
Area ratio of the solder $(\eta_{\text{In edge}})$	60%
Area of the thin disk edge side (A _{side})	$7.854 \mathrm{mm^2}$
Environmental temperature $(T_{\rm E})$	25 (°C)
Initial temperature (T_0)	25 (°C)
Heat sink material	WCu25 alloy
Heat sink size	$\varphi 25 * 2.8 \text{ (mm)}$
Heat sink thermal conductivity $(h_{\rm H})$	200 W/(m•K)
Convective heat dissipation coefficient of impact cooling on the bottom surface of heat sink (q_W)	$20000 (W/m^2 * K)$



FIGURE 7: The simulated and measured temperature of (a) the central and (b) the edge of the thin disk crystal.



FIGURE 8: The edge of the disc crystal after chamfering with a magnification of 100.

cladded, the injected pump power was not higher than 600 W to ensure safety, corresponding to a maximum edge temperature of 350° C (shown in Figure 7(b)). Under this situation, the maximum output power was 195.6 W, with a slope efficiency of 43.0% and a threshold pump power of

about 150 W. Due to the significantly reduced edge temperature without cladding, much more pump power was able to be injected. Finally, a continuous output of 345 W was realized, corresponding to a slope efficiency of 53.6% and a threshold pump power of about 100 W.



FIGURE 9: The edge temperature with and without indium cladding. (a) Without laser. (b) With laser.



FIGURE 10: The center temperature with and without indium cladding. (a) Without laser. (b) With laser.



FIGURE 11: The simulated central temperature rise caused by the heat transfer.

FIGURE 12: The laser output before and after chamfering.

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4. Conclusions

In this paper, the heat generation mechanism on the side of the thin disk crystal was theoretically analyzed and a finite element simulation model was established by using COM-SOL software. Subsequently, the simulations were demonstrated experimentally. The significant difference between measured and simulated data can be described as P < 0.1 at the edge when the measured temperature is lower than the melting point of the metal cladding, and P < 0.05 at the pump area, which proved the correctness of the model. Finally, the influence of the metal absorption cladding on the thin disk laser operation was studied. The thermal caused by the fluorescence absorption of the edge indium cladding reduced by 20% of the opt.-opt laser conversion efficiency, respectively. This result implies that metal absorption cladding, as a commonly used anti-ASE method, needs to pay attention to the influence of the thermal effect on the laser conversion efficiency in the design.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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