Thermal management of water-cooled 10 Hz Yb:YAG laser amplifier

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Abstract： To control the thermal wavefront distortion of repetition frequency laser, we′ve developed a water-cooled active-mirror laser amplifier, which was uniformly cooled from the rear of crystal disk. The numerical anslysis and experimental study on the characterstics of the amplifier's thermal distortion were carried out. It was found that the thermal distorition devoted a significiant modulation to the near field of the laser when the average pump power density was as high as 200 W/cm^2 with the operation frequency of 10 Hz. Near-field modulation would bring a risk to damage the amplifier. To eliminate the modulation of thermal distortion in the near field, two approaches were taken. Firstly, the pump intensity distribution was homogenized, then the edge thermal balance control was carried out. The near field modulation from thermal wavefront distortion was eliminated by these means, a four-pass amplifier with water-cooled laser heads ran well at 10 Hz. The focal spot of output laser was smaller than 5 diffraction limits without any compensation.

Key words： laser amplifiers； diode-pumped lasers； thermal effects； water-cooled active mirror

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High-repetition-rate nanosecond lasers can be used for inertial fusion energy, high energy density physics, strong field physics, high energy and high brightness X-ray source, or high energy and high brightness particle beams. Yb^{3+} doped laser medium has the advantage of low heat generation[1-2], which makes it the most popular active ion for such high power repetition-rate lasers[3]. However, Yb:YAG has a high pump saturation intensity of 28 kW/cm^2 at room temperature. A high pumping intensity is thus needed to improve its optical efficiency. Hence, in spite of its low quantum defect, high thermal loading still arises; moreover, the laser's performance depends on the Yb:YAG crystal's temperature. At low temperature, the Yb:YAG crystal has many advantages such as higher efficiency and better thermo-optic and spectroscopic properties[4]. Accordingly, the Yb:YAG laser was always designed to run at a low temperature: The LUCIA system delivered 14 J at 2 Hz with water-cooled amplifier[5] and the energy deliverded to 30 J at 10 Hz using an active mirror amplifier with tunable helium pressure at the cryogenic temperature[6]; DiOPOLE100 used cryogenic helium gas as the cooling medium and realized 105 J output[7].

Active mirror was a common configuration for repetition frequency laser with mid-level energy output, it has the advantages of high heat transfer efficiency and high uniformity of heat transfer on surface. Table 1 lists some typical active mirror lasers with different output energy and frequency. Table 1 shows that at room temperature, the pump densities of the active mirror lasers were less than 100 W/cm^2, while at cryogenic temperature, the pump density achieved 504 W/cm^2.

Although cryogenic temperature is beneficial to laser output, it also has many disadvatages such as high cost and difficult operation. We hammered at to do our best of a room temperature Yb:YAG laser at 10 J level.

We used the water-cooling method which was cheap and convenient. The laser pulse of about 8.5 J/1 Hz/10 ns was achieved in the primary test in 2014, but at 10 Hz pumping repetition rate, there was a large thermal aberration. As a result, the laser pulse could not pass through the space filter. To reduce the thermal aberration, the reasons were analyzed and several methods were used.

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Table 1 Diode pumped active mirror lasers of several institutions

institution	pump power denisity/(W·cm^{-2})	energy of single laser pulse/ J	output frequency/ Hz	cooling condition
LULI, France	32	14	2	room temperature
	55	30	10	cryogenic temperature
Osaka University, Japan[8]	55	1	100	cryogenic temperature
Industrial Development Center,Japan[9]	37.5	11.5	10	cryogenic temperature
Colorado State University, USA[10]	504	1.5	500	cryogenic temperature
Tsinghua University, China[11]	12	12	10	room temperature
Laser Fusion Research Center of CAEP, China	20	8.5[12]	1	room temperature

In this paper, the influencing factors of thermal effect on the water-cooled active mirror Yb:YAG amplifier were calculated by numerical modeling, and the comparing experiments were conducted.

The 10 J diode-pumped solid-state laser (DPSSL) system in Laser Fusion Research Center (LFRC) was made up of four stages, i.e., the front end, pre-amplifier, boost amplifier and main amplifier. The front end was made up of a fiber oscillator and a fiber power amplifier which were cooled by natural convection. The pre-amplifier was made up of a regenerative amplifier and a two-pass rod amplifier with the laser diodes (LDs) and rods cooled by water together. The boost amplifier and main amplifier were water-cooled active mirror amplifiers and used a four-pass amplifying structure. This paper will discuss the thermal management of the water-cooled active mirror amplifiers.

1 Mechanical structure and numerical simulation of water-cooled back-pumped active mirror amplifier

1.1 Design and analysis of the water cooling structure

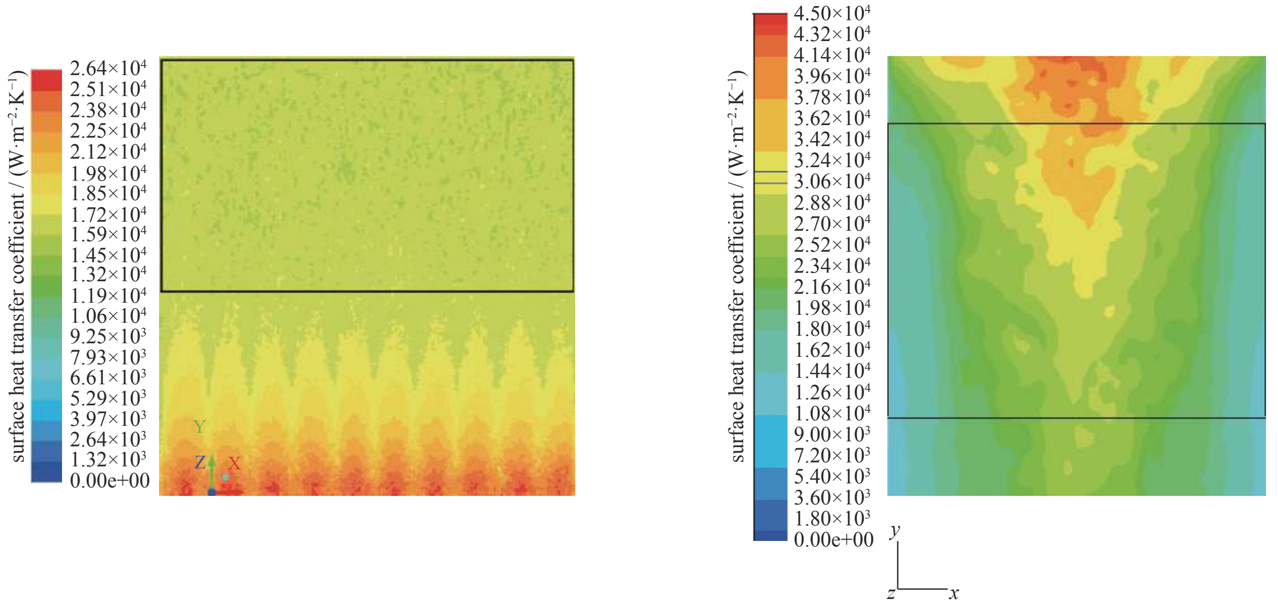
Geuerally, an active mirror amplifier has two alternate structures: the front-pumped structure and the back-pumped structure. We chose the back-pumped structure which could cool the crystal from the side with higher pumping power density to obtain a lower temperature.

Achieving a high and uniform surface heat transfer coefficient is the design goal of the cooling channel in the laser head. To obtain a high surface heat transfer coefficient, the velocity of water flow beside the laser medium must be high. The thickness of the water flow region was optimized to 1 mm which could allow a high flow speed and was not too large to retain high efficiency of pump light. Fig.1(a) is the diagrammatic sketch of the laser head. The pump light passes through the glass and water and then is absorbed by the Yb:YAG crystal. The laser light passes throw the Yb:YAG crystal and then is reflected by the back surface of the Yb:YAG crystal. To make a uniform distribution of velocity, we a designed water viscolizer, which was an array hole plate, as shown in Fig.1(b). The hole is bell-mouthed and the diameter of its narrow end is 2 mm, and the distance of each hole is 4 mm.

(a) laser head (b) water viscolizer

Fig. 1 Diagrammatic sketch of the laser head and mechanical structure of the water viscolizer

The surface heat transfer coefficient on the surface of the laser medium was calculated by CFD software. The surface heat transfer coefficient on the heat transfer surface with the water viscolizer was also calculated, as shown in Fig.2(a). The surface heat transfer coefficient near the inlet was not uniform and it became more and more uniform with the flow extending. To obtain a good heat transfer result, we should put the laser medium on the place where the water was extended enough. The modulation of the surface heat transfer coefficient in the black rectangle of Fig.2(a) is 1.01. To compare the effect of the



(a) with water viscolizer (b) typical simulation result with a simple cube

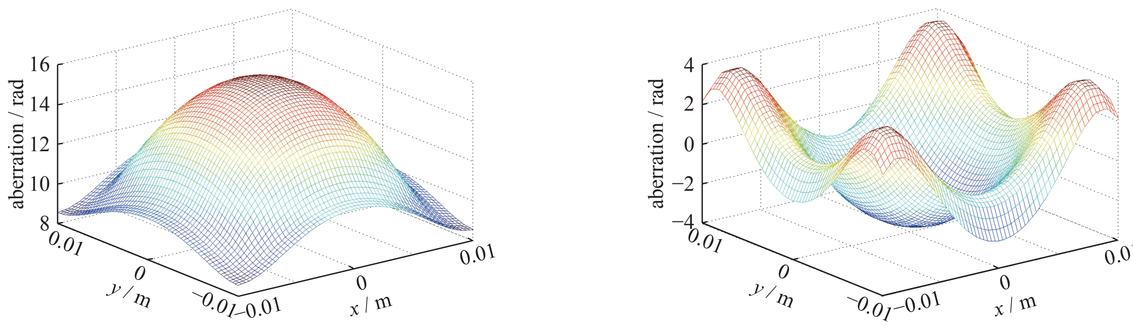
Fig. 2 Numerical results of surface heat transfer coefficient

viscolizer, a typical surface heat transfer coefficient with a simple cube is shown in Fig.2(b). As we can see, there is not a uniform area of surface heat transfer coefficient in Fig.2(b). The modulation of the surface heat transfer coefficient in the black rectangle of Fig.2(b) is 2.17.

1.2 Influence of the pump uniformity and thermal balance on the wavefront aberration

Because the directivity of the laser diodes is not identical, the pump light is not uniform on the cross section of the laser medium. When the pumping frequency is 1 Hz, the modulation of pumping will only impact on the near field of the laser. However, when the pumping frequency is 10 Hz, the modulation of pumping light will impact not only on the near field but also on the wavefront which makes the near field more inhomogeneous and affects the focusability performance. In reference [13], we analyzed the influence of pumping on the temperature and thermal stress and the results showed the impact was significant.

There are two main sources of thermal distortion in the laser medium. One is the refractive index vehicle caused by temperature difference. The other is the deformation of the medium caused by thermal expansion. Because the edge of the medium has a pump light blank period and ASE light heating cladding materical, the thermal distortion of the edge part of the laser medium is prone to mutation. In the simulation, we defined the pump power density to 200 W/cm^2, the size of the Yb:YAG crystal was 20 mm×20 mm, the size of pump beam was 14 mm×14 mm. the thermal distortion caused by temperature difference and deformation was analyzed. The results of the analysis are shown in Fig.3.



(a) distortion caused by temperature difference (b) distortion caused by deformation

Fig. 3 Numerical results of wavefront distortion

From the analysis results, it can be seen that the wavefront distortion caused by deformation is opposite to the distortion caused bu temperature difference on a large surface and distortion caused by deformation has inflection points at the four edges. These inflection points will cause fast modulation on the near field. We need to eliminate the inflection points of edge wavefront distortion by thermal balance.

2 Experimental research

2.1 Experimental study on the effect of pump uniformity on beam quality

In the main amplifier, there were two laser heads pumped by 60 kW LD respectively. The directivity of the fast axis of the LD array was not very good, which made the modulation of pumping intensity deep. At first, the modulation ratio(defined as the ratio of the peak intensity to the average intensity in the near field) of the pumping intensity was larger than 1.5 (Fig.4(a)). When the laser ran at 1 Hz, the pump distribution just affected the near field, the phase aberration was not obvious (Fig.4(b)). But when the laser ran at 10 Hz,the effect on phase aberration was very large, the near field was modulated obviously, as it is shown in Fig.4(c), the beam was modulated from a square to a line. In this experiment, the signal light was set before the pump light temporally to avoid the gain modulation of the beam.

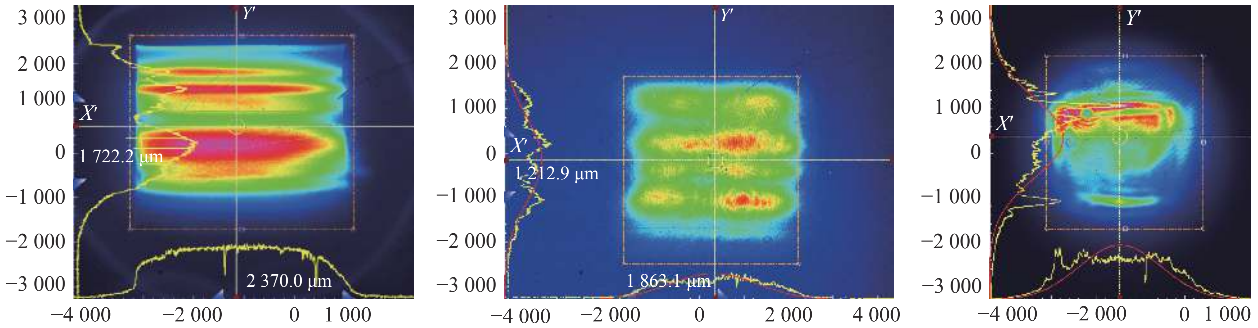
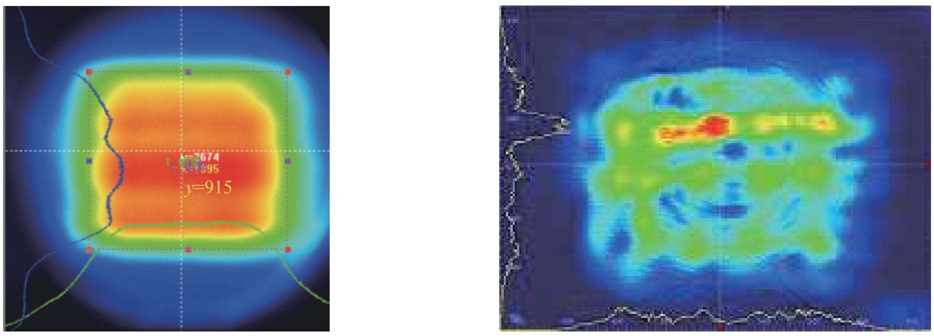


Fig. 4 (a) near-field distribution of the pump, (b) near field of output laser with 1 Hz pumping and (c) near field of output laser with 10 Hz pumping

To reduce the modulation of the pump, two methods were used. One was to change the cylindrical lens to prism, which added the randomness of LD light to the pumping surface. Because there were two amplifiers in this stage, the other method was changing the permutation and combination of the pumping LD arrays to obtain the most uniform pumping distribution. Using these two methods, the pumping distribution for the two amplifiers was improved to 1.26 and 1.31 respectively. After optimizing the pumping distribution, the near field the output laser was more uniform, as shown in Fig.5(b). The output energy was 7.1 J at 10 Hz under these conditions.



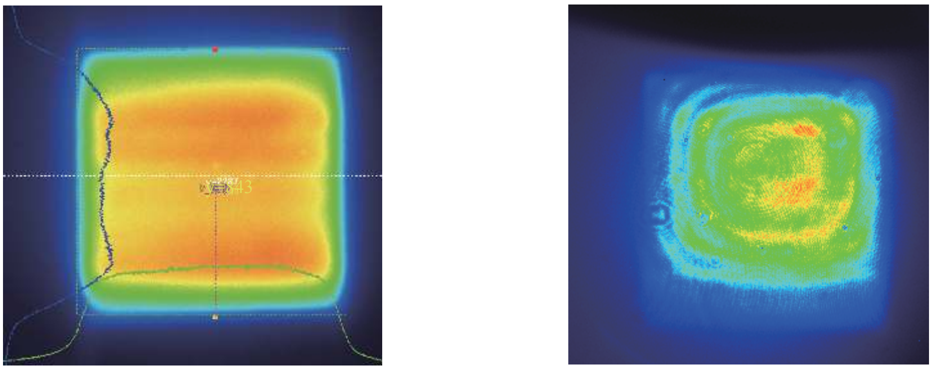
(a) (b)

Fig. 5 (a) near-field distribution of the pump after optimization and (b) near field of output laser

The boost amplifier is made up of one laser head with a water-cooled active mirror Yb: YAG crystal which is pumped by a 10-Hz 40-kW LD array from the back surface of laser. The pumping area was 12 mm×12 mm, the peak pumping power density was 20 kW/cm^2, the pumping frequency was 10 Hz and the average pumping power density was 200 W/cm^2. The modulation ratio of the near field was 1.16 for the pump light. Using a ϕ35 mm Yb:YAG disk, the near field of the laser was modulated by the high frequency wavefront aberration. Fig.6 shows the near field after the amplifier and there are rings on the edges of the laser. After four-pass amplification, the modulation became deeper and more mussy.

As you can see, although the pump distribution was very good, the near field of the laser was not very flat. The transverse modulation caused by the pump disappeared, but there was still a ring modulation.

We can draw a conclusion that uniform pumping has significant benefits for improving beam quality, but it is far from enough when the pumping is 10 Hz.

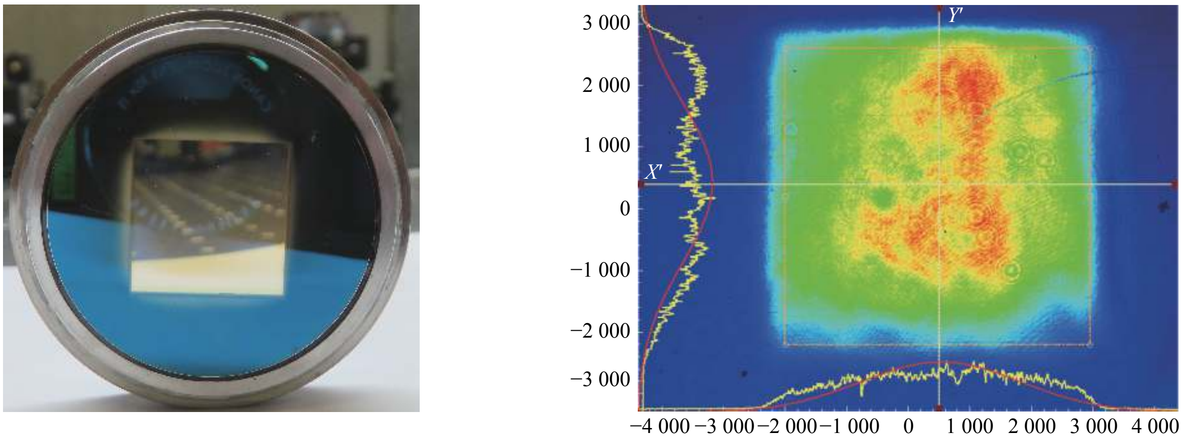


(a) pumping distribution (b) near field

Fig. 6 Pumping distribution and near field after one-pass amplification for a ϕ35 mm disk

2.2 Experimental study of edge thermal banlance

According to the influence of edge heat balance on wavefront distortion, we carried out experimental study. Two methods were used to realize the edge heat balance. One method used Yb:YAG crytal cladded with Cr^{4+}:YAG ceramics. The crystal and ceramaics were combined by a linkage of good heat transfer. The size of the crystal was 20 mm×20 mm, and the size of pump beam was 12 mm×12 mm. With this method, the wavefront distortion caused by thermal was controlled very well and the output near field had no ring modulation. Fig.7 shows the photo of the laser medium and the near field of the output laser.



(a) (b)

Fig. 7 (a) Cr^{4+}:YAG ceramic cladded Yb:YAG crystal, (b) near field after four-pass amplification

The other method used Yb:YAG crystal glued with Cr^{4+}:YAG crystals. The two kinds of crystals were glued with each other by a glue of about 0.5 mm in thickness and little heat transfer. In this condition, it is found that the thermal distrotion was not sensitive to the parameters of Cr^{4+}:YAG but sensitive to the matching degree of the size of the Yb:YAG crystal and the pump beam. When we used a 20 mm×20 mm crystal and a 12 mm×12 mm pump beam, there was modulation, as shown in Fig.8(a). When we used a 16 mm×14 mm pump beam,the thermal modulation on the 16 mm direction disappeared, as shown

(a) 20 mm×20 mm crystal with 12 mm×12 mm pump beam (b) 20 mm crystal with 16 mm×14 mm pump beam

Fig. 8 Near field picture of different size matching degree in Fig.8(b). We cut the crystal to 18 mm×16 mm and used the 16 mm×14 mm pump size and measured the near field, the ring modulation disapperaed, as shown in Fig.9.

After adopting the edge heat balance technique, the whole system experiment was carried out. The near field of the output laser was measured, which was shown in Fig.10(a). The wavefront of output laser was measured by the Shack-Hartmann sensor and the result is shown in Fig.10(b). The far field was measured by a CCD. The evaluation shows the far field quality is less than 5 diffraction limits (DL) (see Fig. 10(c)).

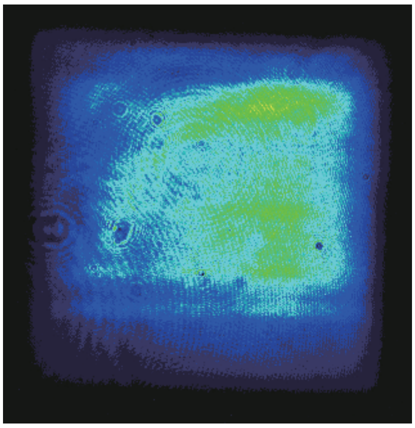
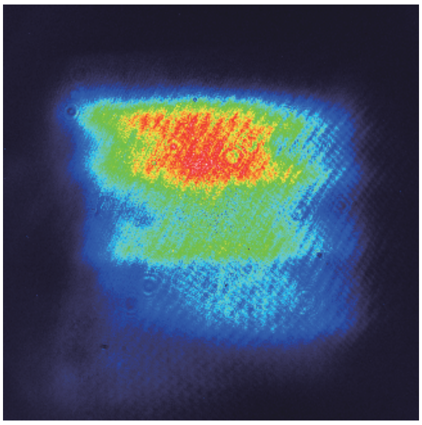


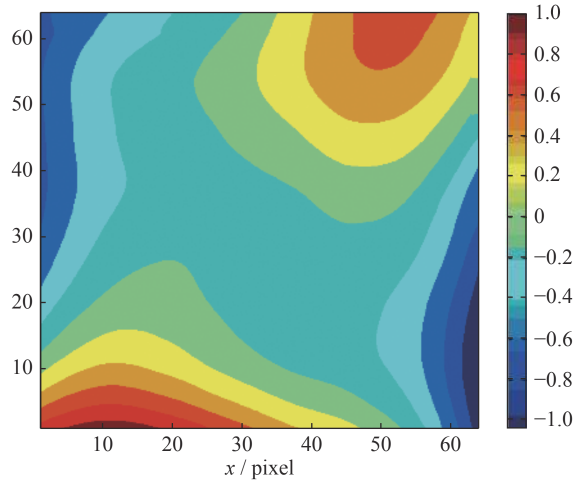
Fig. 9 Near field picture of 18 mm×16 mm crystal pumped by 16 mm×14 mm beam

3 Conclusion

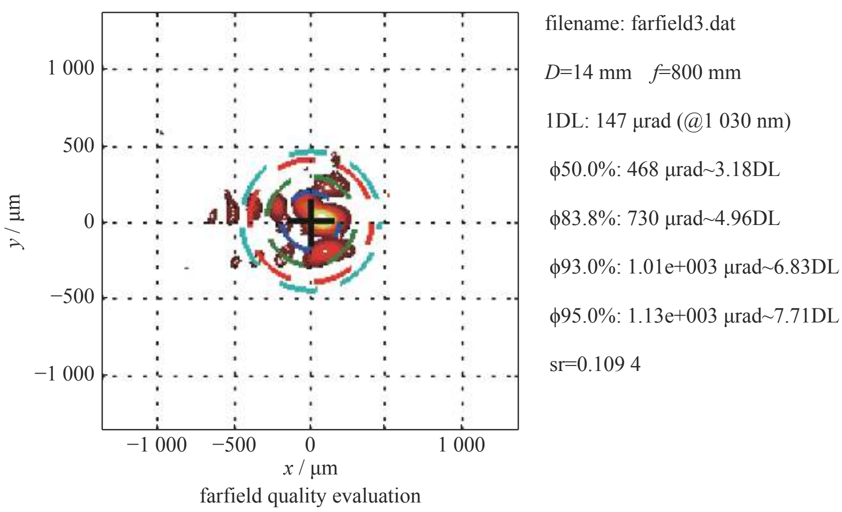
The design of water-cooled laser heads and the methods to obtain a uniform near field were introduced. To obtain a good beam quality, the pumping distribution and the structure of crystal were optimized. With high power density pumping at room temperature, the focal spot was less than 5 diffraction limits without compensation in a 10-Hz Yb:YAG laser. The pump density was as high as 200 W/cm^2, which was the highest power density of a room temperature active mirror laser to our knowledge. Through this study, some useful conclusions can be obtained: To achieve good thermal management effect, uniform cooling and pumping distributions are very necessary, but under strong



(a) near field



(b) wavefront aberration



(c) far field and evaluation

Fig. 10 Beam quality parameters of output laser pumping, these are far from enough. Matching of pump light with material aperture is a crucial factor. Although Yb:YAG laser operating at room temperature is not very efficient, the conclusions of this paper have a strong reference value for high repetition rate laser operating at both room temperature and cryogenic temperature.

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水冷 10 Hz Yb:YAG 激光放大器热管理

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摘 要： 为了控制重频放大器的热致波前畸变，设计并加工了均匀冷却的背面水冷激活镜激光放大器，对放大器的热畸变特性开展了实验研究，实验发现在泵浦功率密度较高即重复频率达到 10 Hz，平均功率密度达到 200 W/cm^2 时，放大器的热畸变既影响远场分布又对近场产生显著的调制。近场的调制会给放大器带来较大的损伤风险。为了消除热畸变对近场的调制，首先对泵浦强度分布进行了匀化，然后对介质进行了边缘热平衡控制，消除了热畸变引起的近场调制。通过对上述因素的控制，采用水冷激活镜构型的四程放大器实现了在 10 Hz 频率下良好运行。在没有进行主动补偿的情况下，实现了远场焦斑优于 5 倍衍射极限的输出。

关键词： 激光放大器；二极管泵浦激光器；热效应；水冷激活镜