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A study on the amplification of active-mirror Yb:YAG lasers

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Abstract

Thermal effects and amplified spontaneous emission (ASE) are two main factors in the design of high-power and high-energy laser amplifiers. The temperature distribution and the lateral ASE of the face-pumped active-mirror Yb:YAG amplifiers are analyzed with finite element analysis software. An amplifier with an output energy of 100 J was designed to illustrate energy scaling of the face-pumped active-mirror structure.

Keywords: Thermal effect; lateral ASE; active-mirror; energy scaling

1. Introduction

With the development of laser diodes, Yb:YAG amplifiers are a great potential material for obtaining high-power and high-energy laser output because of their high quantum efficiency, long fluorescence lifetime, broad emission and excellent thermos-mechanical properties (Bruesselbach, H.W., *et al.*, 1997; Chanteloup, J.C. & Albach. D., 2011; Fan, T.Y.,1993; Furuse, H., *et al.,* 2014). A number of research studies have been published that detail the high-power diode-pumped Yb:YAG solid-state laser systems (Zhu, G., *et al.,* 2014; Banerjee, S., *et al.,* 2012; Green, J.T., *et al.,* 2014; Hakobyan, S., *et al.,* 2016; Endo, A., *et al.,* 2014; Siebold, M., *et al.,* 2016)). The research indicates that performance of Yb:YAG lasers strongly depends on temperature because of the quasi three-level system((Divoky, M., *et al.,* 2014; Gonçalvès-Novo, *et al.,* 2013). At room temperature, intense pumping is needed to obtain a high gain because of the re-absorption of the lower energy-level. This increases the complexity of the laser system (Nishio, M., *et al.,* 2014; Chen, X., *et al.,* 2016). The thermal-optic properties of Yb:YAG amplifiers, such as thermal conductivity and emission cross-section, can be improved by decreasing the temperature. However, the ASE of Yb:YAG will deteriorated, and the damage threshold of the optical coating will decrease at lower temperatures (Gonçalves-Novo, *et al.,* 2014; Marrazzo, S., *et al.,* 2016; Körner, J., *et al.,* 2014).

The management of thermal effect and amplified spontaneous emission (ASE) is a major issue in high-power solid-state lasers oscillator and amplifier design (Speiser, J., 2009; Peterson, P., *et al.,* 2011). In this paper, the temperature distribution and lateral ASE of the active mirror Yb:YAG are analyzed. Then a laser amplifier with an output energy of 100 J is designed to illustrate the energy scaling of the active-mirror Yb:YAG.

2. Temperature distribution of active-mirror Yb:YAG

A typical structure of the faced-pumped active mirror Yb:YAG laser is shown in Fig.1. Pump light with a center wavelength of 940 nm enters the Yb:YAG crystal from one big surface (S_1). Another big surface (S_2) is the cooling surface, which is wrapped by a thin indium (In) layer. To reduce thermal distortion on the surface, an undoped YAG is usually bonded with the doped Yb:YAG (Fig. 1). Metals, such as copper (Cu) and aluminum (Al), are usually used to make the heat sink because of their high thermal conductivity. The incident light with a center wavelength of 1030 nm enters the Yb:YAG at a certain angle (θ).

To study the thermal performances of the Yb:YAG at different cooling temperatures, the temperature distribution of the Yb:YAG is analyzed at different cooling temperatures. In the calculation, the thermogenesis efficiency is 0.1 and the absorbed pump power is 1000W. This means that the heat generation in the Yb:YAG is 100 W. The size of the Yb:YAG is Φ30×3.5 mm with a doping concentration of 4 at.%. The thermal conductivity of the Yb:YAG crystal is 25, 15.5, 11.8, 9.6 and 8.2 W/mK respectively when the cooling temperature is 100 K, 150 K, 200 K, 250 K and 300 K, based on the experiments and some references (Aggarwal, R.L., 2005). Based on research by Aggarwal *et al.* (2005), thermal conductivity of the Yb:YAG crystal and the temperature are related as in Table 1.

In the analysis, the surface S_2 is assumed to be the only cooling surface of the Yb:YAG. This means that the side surface and the surface S_1 are both heat insulated. The heat sink is assumed to have enough ability to dissipate heat, so the temperature of the surface S_2 is equal to that of the cooling liquid. Fig. 2 shows the temperature distribution in the Yb:YAG crystal with different cooling temperatures at

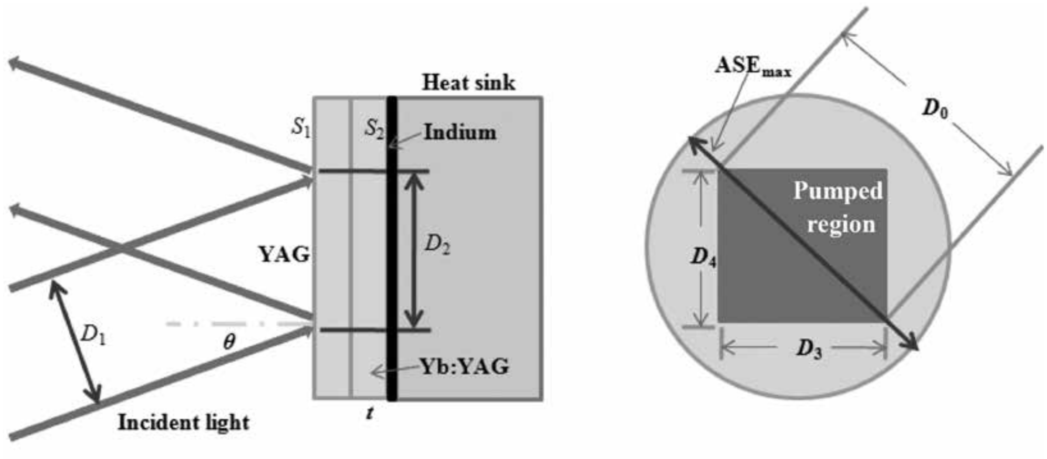


Fig. 1. Pump and cooling structure of active-mirror Yb:YAG amplifier

the same pump power. The maximum temperature occurs at the surface S_1 and decreases as the cooling temperature is lowered (Fig. 2). When the cooling temperature is 300 K, the maximum temperature at the surface S_1 is 343.47 K, and when the former reduces to 100 K, the latter reduces to 114.26 K. In addition, Fig. 3 shows that with an increase in thermal conductivity, the temperature difference will obviously reduce as the cooling temperature decreases. This helps reduce thermal stress and the thermal stress birefringence (Koechner, W., 2013).

3. Amplification characteristics of active-mirror Yb:YAG

The amplified spontaneous emission (ASE) is another factor limiting the output power of a Yb:YAG amplifier. For the active-mirror structure of a Yb:YAG amplifier, the magnification of the amplifier is limited by the lateral ASE. As shown in Fig. 4, the incident light is amplified after passing the pumped region. At the same time, the lateral ASE can also be produced at any direction, and the diagonal length (D_0) involves the longest distance of lateral ASE (Fig. 1). Thus, in amplifier design, the product of the small signal gain (g_0) and D_0 cannot be too large, although g_0 increases rapidly because the emission cross section of Yb:YAG increases significantly when the cooling temperature declines.

Table 1. Relationship of thermal conductivity and cooling temperatures for Yb:YAG crystal (Aggarwal *et al.* 2005)

Temperature in K	Thermal Conductivityin W mK
100	25
150	15.5
200	11.8
250	9.6
300	8.2

Some researchers have studied the theoretical calculation of the small signal gain in Yb:YAG amplifier(Zapata,L.E., *et al.,* 2015; Sekine, T., *et al.,* 2016). We designed an experiment to confirm the amplification characteristics of the active-mirror YAG/Yb:YAG at different cooling temperatures (Fig. 4(a)). The laser diode produces 3 J pulse energy with a repetition frequency of 10 Hz and a center wavelength of 940 nm. The pump light shaped by three lenses enters the YAG/Yb:YAG from the big surface S_1, and the incident light enters the Yb:YAG with an angle of 10°. The flat and totally reflecting M1, λ/4 wave plate and polarizer are used to ensure that the incident light passes the Yb:YAG twice. The energy of the incident light is 6 mJ with a size of 4.5 mm×4.5 mm. The size of the pump light is 5.5 mm×6.5 mm. The

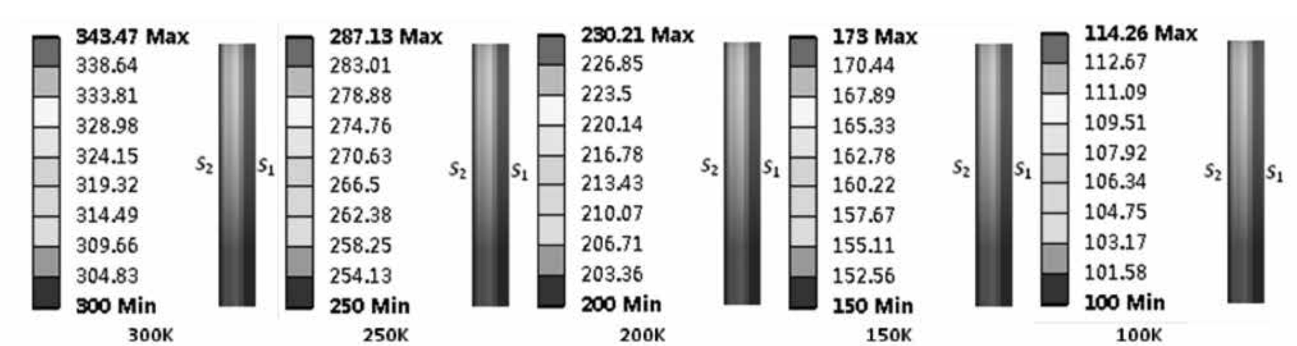


Fig. 2. Temperature distribution of Yb:YAG at different cooling temperatures

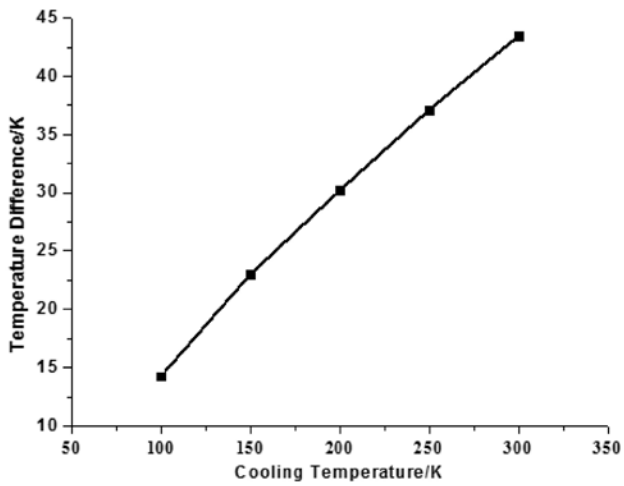


Fig. 3. Maximum temperature differences in Yb:YAG at different cooling temperatures

thicknesses of the YAG and Yb:YAG are 3.5 mm and 3 mm, respectively, with the doping concentration of 4 at.%. Fig. 4(b) shows the magnification (G) of the Yb:YAG amplifier at different cooling temperatures when the pump energy is 3 J. As the cooling temperature declines, the magnification increases up to 150 K. Because of the lateral ASE, it decreases when the temperature decreases. The small signal gain can be calculated by the formula $G=Exp(g_0 l)$. Then the product of the small signal gain (g_0) and the diagonal length (D_0) can also be calculated. In our experiment, the g_0D_0 is about 2.5 at 150 K. Base on work by Kouznetsov *et al.* (2009) and Mason *et al*. (2011), and with the suppression methods of ASE and parasitic oscillation, such as edge-cladding technology, the small signal gain is limited by $g_0D_0<G_{ASE}=3$ in our concept of laser amplifiers.

4. The Yb:YAG amplifier design with 100 J output energy

In previous research, a maximum output energy of 6.05 J with a pulse width of 10 ns was obtained from a liquid nitrogen cryogenic cooling active-mirror Yb:YAG amplifier system (Cheng *et al.* 2015). To identify the amplification of the Yb:YAG with the active-mirror structure, an amplifier with an output energy of 100 J at a repetition frequency of 10 Hz and a pulse width of 10 ns was designed. This incident light energy was 6 J. As shown in Fig. 5, two stage amplifiers create the output energy of 100 J. In the first amplifier, the seed pulse is boosted to 30 J, and then the output energy is 100 J after entering the second amplifier.

The cooling temperature of the Yb:YAG was 150 K, which is considered suitable (Cheng *et al.* 2015). The doping concentration and the thickness of the Yb:YAG is related to the energy storage. Based on the laser rate equations and pulse amplification characters, the net energy store fluence versus the product of the doping concentration (α) and thickness (t) were calculated (Fig. 6(a)). At first, the net energy store fluence increases rapidly as the product of α and t increases. However, the increase slows after the product of α and t reach 1.5, which means that more improvement of the doping concentration or thickness of Yb:YAG cannot bring more energy storage. The smaller thickness helps thermal dissipation. So in our concept, the product of α and t is equal to 1.5. The small signal gain (g_0) versus αt can also be calculated. When αt is equal to 1.5, the small signal gain is about 0.34/cm at 150 K (Fig. 6(b)).

To ensure the safety of the optical device, the high output flux of the amplifier should be less than 3 J/cm^2, so

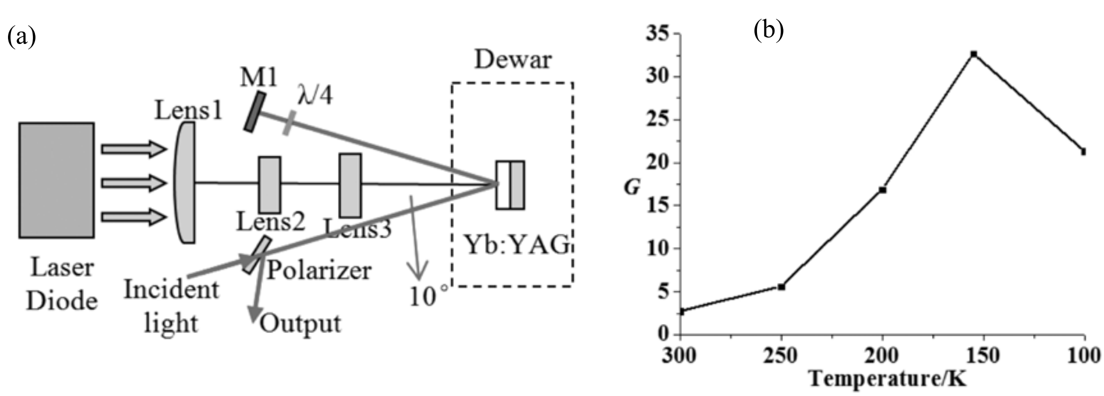


Fig. 4. (a) Sketch map and magnification of the active-mirror Yb:YAG amplifier (b) relationship between magnification and temperature

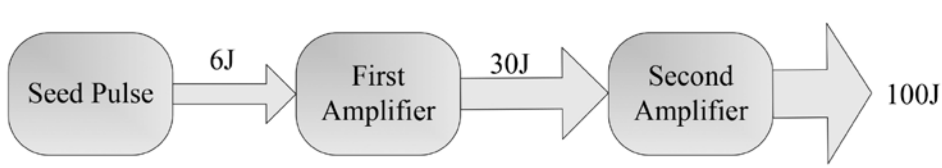
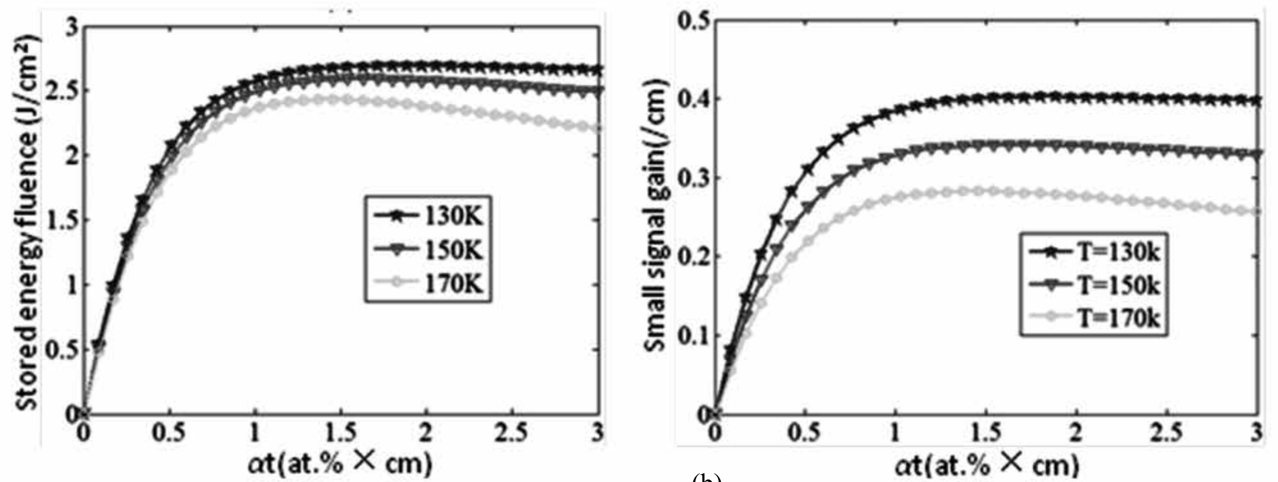


Fig. 5. Two stage amplifiers



(a) (b)

Fig. 6. Net store energy fluence (a) and small signal gain (b) versus the product of doping concentration (α) and thickness (t) of Yb:YAG

the laser spot size ($D_1 \times D_2$) of 30 J and 100 J is designed to 3.2×3.2 and 6×6 cm. With this design, the highest energy density of the output power is 2.93 and 2.78 J/cm^2.

For the pump light, as shown in Fig. 1, the dimension D_3 is equal to D_2, and D_4 can be calculated by the size, the angle of incident light, and the thickness of Yb:YAG. In our design, the angle of the incident light is 10°. The rule of $g_0 D_0 < G_{ASE} = 3$ is obeyed because of the need to restrain the ASE in our system. This is based on results from aforementioned experiments. Therefore, for the 100 J system, the dimension of D_3 is 6.5 cm, and the thickness of the Yb:YAG is 1 cm. This means that the doping concentration is 1.5 at.%. Fig. 7 shows the output energy at different pump energy levels when the incident light energy is 30 J and the cooling temperature is 150 K. A total pump energy of 220 J is needed to obtain the 100 J energy output. The amplifier with an output energy of 30 J can be designed with the same method. Table 2 shows the main parameters of 30 J and 100 J amplifiers.

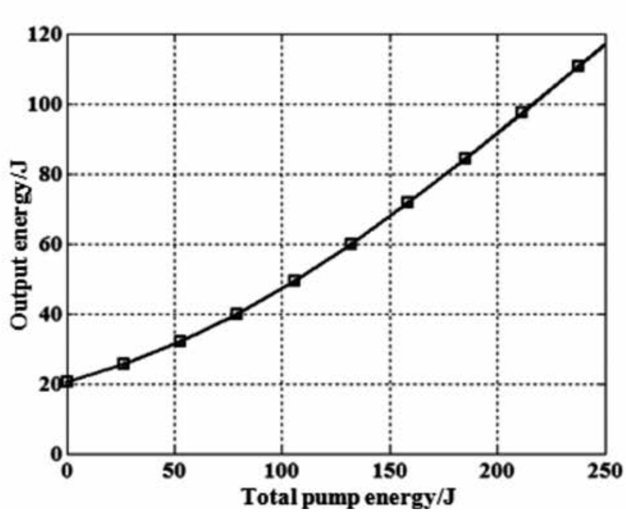


Fig.7. Output energy at different total pump energy levels

Table 2. Parameters of amplifier designs

Output energy (J)	30	100
Incident light energy (J)	6	30
Total pump energy (J)	100	220
Doping concentration (at. %)	2	1.5
Thickness of the Yb:YAG (cm)	0.75	1
Work temperature (K)	150	150
Size of incident light (cm)	3.2×3.2	6×6
Pump area (cm)	3.2×3.5	6×6.5
Output flux (J/ cm^2)	2.93	2.78

5. Conclusion

The analysis and calculation show that the face-pumped active-mirror Yb:YAG have good performances on power-scaling at low temperatures, as long as the product of the small signal gain and the diagonal length of the pump area are limited to reasonable values. The size of the laser material is the only factor that limits the acquisition of a higher output power or energy. Fortunately, the development of transparent laser ceramics has made available new techniques that will allow for large-sized materials with a low scattering loss. Moreover, it is easier for the ceramic to restrain the ASE and parasitic oscillation than for the crystal because of the fabrication technology of the laser ceramic. Predictably, the face-pumped active-mirror Yb:YAG amplifiers can produce a higher energy laser.

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دراسة عن تضخيم المرآة النشطة Yb:YAG لأشعة الليزر

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الملخص

تعتبر التأثيرات الحرارية والانبعاثات العفوية المضخمة (ASE) عاملان رئيسيان في تصميم مضخمات الليزر ذات القوة والطاقة العالية. تم استخدام برمجيات تحليل العناصر المحدودة لتحليل التوزيع الحراري والانبعاثات الجانبية المضخمة لمضخمات Yb:YAG. تم استخدام المضخم الذي ينتج طاقة 100 جول لتوضيح قياس الطاقة لهيكل المرآة النشطة.