Results in Physics 8 (2018) 281–285

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

Investigation on efficiency declines due to spectral overlap between LDAs pump and laser medium in high power double face pumped slab laser

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ARTICLE INFO

Article history:
Received 8 September 2017
Received in revised form 27 November 2017
Accepted 28 November 2017
Available online 7 December 2017

ABSTRACT

In high power diode lasers, the input cooling water temperature would affect both output power and output spectrum. In double face pumped slab laser, the spectrum of two laser diode arrays (LDAs) must be optimized for efficiency reason. The spectrum mismatch of two LDAs would result in energy storing decline. In this work, thermal induced efficiency decline due to spectral overlap between high power LDAs and laser medium was investigated. A numerical model was developed to describe the energy storing variation with changing LDAs cooling water temperature and configuration (series/parallel connected). A confirmatory experiment was conducted using a double face pumped slab module. The experiment results show good agreements with simulations.

Introduction

Diode-pumped laser systems are capable of delivering laser pulses with multi-joule to kilo-joule output energy with good beam quality and high efficiency, due to the development of high power, high efficiency and high temperature diode laser with narrow spectrum width [1–3]. In laser diode arrays (LDAs), considering the electrical-to-optical conversion efficiency and the heat removed through the heat sink, a large amount of power loss leads to a considerable increase of temperature in the active zone of the laser diode under high-power operation, resulting in the changing of output characteristics, such as threshold current shifting, efficiency decline, and emission wavelength drafting [4–8]. Because of material refractive index shift, gain peak wavelength and other reasons, the diode lasing wavelength undergo the red shift with the temperature increasing. With effective thermal mounting of laser diode to a heat sink, the output characteristic could be stabilized in an acceptable region when laser diode works at high output power. Also, the liquid cooling scheme is widely used in the high power LDAs. When changing the flow rate and temperature of cooling water, the emission spectrum property and output power of LDAs could be different.

Nd:YAG, which is suitable to be pumped with LDAs [9–11], is one of the most developed laser gain material since the first demonstration. Among all types of Nd:YAG lasers, as one of the most promising pathway to high power and high energy lasers, the slab lasers are widely investigated [12–15]. In face pumped Nd:YAG zigzag slab laser, the two total internal reflection (TIR) faces are used as both pumping and cooling [16–20], and typically, two LDAs are used for pump. The Nd:YAG absorption bandwidth at 808 nm is less than 4 nm [21,22], which demands that with LDAs as pump, the emission wavelength and bandwidth of LDAs must be controlled and meet with the absorption spectrum of Nd:YAG. In a typical GaAlAs structure used for pump, the spectrum peak emission changes 0.3 nm/K, which makes temperature control important in a diode pumped Nd:YAG laser. Under high power operation, the drifting of the LDAs wavelength will lead to the significant output power and stability reduction. In slab laser modules with two LDAs as pumps, the emission peak wavelength and bandwidth should all be optimized for maximum energy storing efficiency. The two LDAs usually cooled with separate input cooling water, which make two LDAs work at almost the same temperature. However, in some compact laser applications, the two cooling water pipes of LDAs have to be connected in series, resulting in the input cooling water temperature rising of the second LDAs and finally the decline of the laser power.

In this paper, Thermal induced efficiency declines due to spectral overlap between high power LDAs pump and laser medium in double face pumped slab laser were investigated theoretically

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https://doi.org/10.1016/j.rinp.2017.11.034
2211-3797/

and experimentally. A numerical model was proposed to compute the overlap efficiency between the pump and gain medium spectrum with different LDAs cooling conditions. The energy storage under two LDAs with different input cooling water temperature differences were computed with numerical model, The experiment results show good agreement with simulation results. It found that with the cooling water temperature varying from 24 °C to 28 °C, and two LDAs input temperature difference of 2 °C, the energy storing efficiency decreased by 16.94% than the maximum. This work could be useful for design of compact high power and high energy Nd:YAG slab laser that uses high power LDAs as pump.

Numerical model and simulation

A numerical model was proposed to compute the overlap efficiency between the pump and Nd:YAG laser gain medium in different cooling conditions.

To compute the total absorption power, the absorption spectrum of Nd:YAG laser gain medium should be obtained first. A typical absorption spectrum (normalized) was shown in Fig. 1. The absorption peak was at 808.4 nm.

The LDAs output power and emission spectrum were experimentally tested under different input cooling water temperatures, and shown in Fig. 2a) and b). The cooling temperature and thermal effect would not only affect the emission peak, but also output power and FWHM. Before the slab amplifier assembled, the LDAs pump output property, including emission spectrum peak, spectrum FWHM, and output power, were experimentally tested under different cooling condition. The experiment results show that the output peak shows red shift versus temperature. The experiment results are identical with laser diode theory. This test results would be used in the simulation. In the simulation, we assumed that the pump laser originating from two LDAs had the same temperature property (output power and emission spectrum versus cooling water temperature).

To obtain the total absorbed power, the absorption efficiency with different wavelengths should be computed first. The maximum LDAs output power was about 632 W, and the work repetition rate and the output pulse width were 200 Hz and 250us. The peak pump power was about 12.6 kW. In used Nd:YAG slab amplifier, the pump area was 30 mm × 120 mm, the single side pump intensity could be obtained as 350 W/cm^2 and double side total pump intensity about 700 W/cm^2, which are much smaller than the saturation pump intensity of 2.9 kW/cm^2. The pump saturation effect is negligible. The absorption coefficient of active medium and the emission power spectrum of LDAs could be expressed in Eqs. (1) and (2). Note that w(λ) is the normalized LDAs emission spectrum.

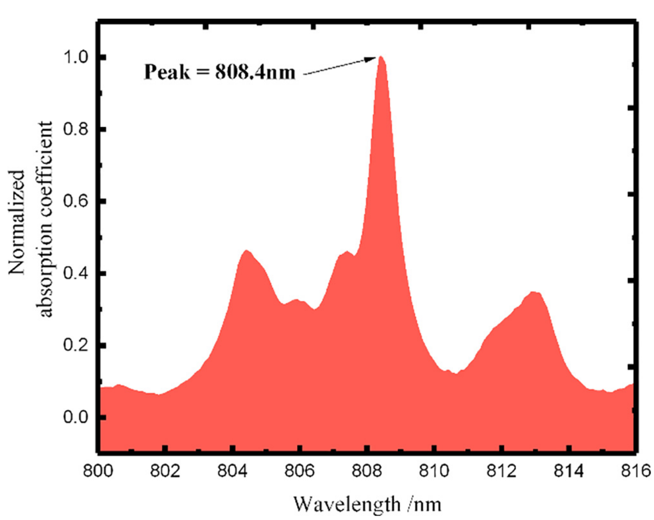

Fig. 1. An typical absorption spectrum (normalized) of Nd:YAG. The absorption peak was at 808.4 nm.

$$\alpha_{medium} = \alpha(\lambda) \tag{1}$$

$$P_{LDAs} = P_0 w(\lambda), \int w(\lambda)d\lambda = 1 \tag{2}$$

Note that the emission spectrum could be approximated to Gaussian distribution, but the standard deviation ($1/e^2$ width) of the Gaussian distribution is not equal to the FWHM. The FWHM is 1.6 times of standard deviation of Gaussian distribution as shown in Eq. (3).

$$FWHM = 1.6 \times \sigma, \tag{3}$$

So w(λ) could be expressed as:

$$w(\lambda) = \frac{1}{\sqrt{\pi} \times FWHM/1.6} exp\left(-\frac{(\lambda - \lambda_{peak})^2}{(FWHM/1.6)^2}\right) \tag{4}$$

Then the deposited power in the gain medium could be calculated according to Beer-lambert law of absorption:

$$P = P_0(1 - exp(-\alpha l)), \tag{5}$$

Substitute Eqs. (1), (2) and (4) into Eq. (5), and integrate over the wavelength, then the total absorbed power could be obtained as:

$$\begin{aligned} P &= \int P_0 w(\lambda) \times (1 - \exp[-\alpha(\lambda)])d\lambda \\ &= P_0\left(\int w(\lambda)d\lambda - \int w(\lambda)\exp[-\alpha(\lambda) \cdot l]d\lambda\right) \\ &= P_0\left(1 - \int w(\lambda)\exp[-\alpha(\lambda) \cdot l]d\lambda\right) \end{aligned} \tag{6}$$

Eq. (6) could be used for laser medium deposited power computation using two LDAs with different water cooling temperature. At the end of the pump pulse, the storage energy was directly proportional to the absorbed pump power. The small signal gain and other amplifier characteristic were investigated in our previous work [20].

In simulation, the absorbed power was considered under three different cooling conditions, that two LDAs with input cooling water temperature differences of 0 K, 1 K and 2 K, respectively. The spectrum overlap demonstration under three different conditions were shown in Fig. 3. The mismatch of the emission and absorption spectrums would result in the decline of power absorption and energy storing of the slab gain medium.

Experiment setup

A confirmatory experiment was conducted to measure the energy storing of slab laser amplifier module under different cooling conditions. The experiment results could reveal the thermal dependence of overlap between LDAs pumps and gain medium. The energy storage is one of the most important parameters for high power pulse laser amplifier. The absorbed pump power could be directly represented by energy storage. So, in our study, we chose energy storage parameter to investigate absorption efficiency.

The large face diode pumped slab amplifier module [20] used in experiment was developed by Academy of Opto-Electronics (AOE), Chinese Academy of Science (CAS). The laser was zigzag propagating inside the slab module. In our experiment, the module was

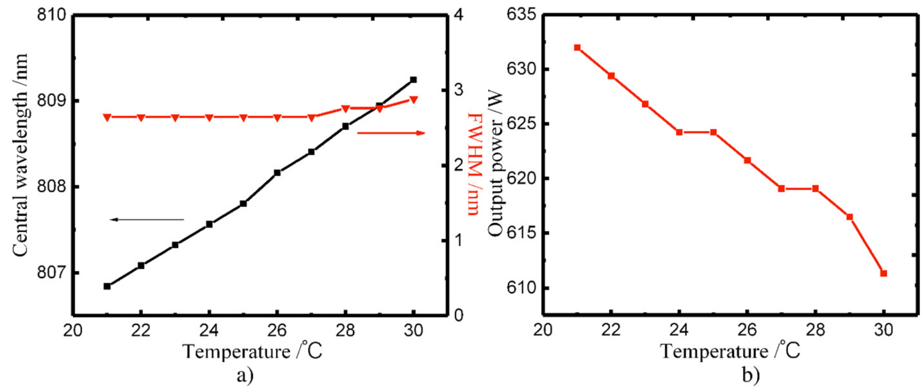

Fig. 2. Temperature property of LDAs, a) output spectrum peak wavelength and FWHM and b) output power as function of temperature under the same pump current.

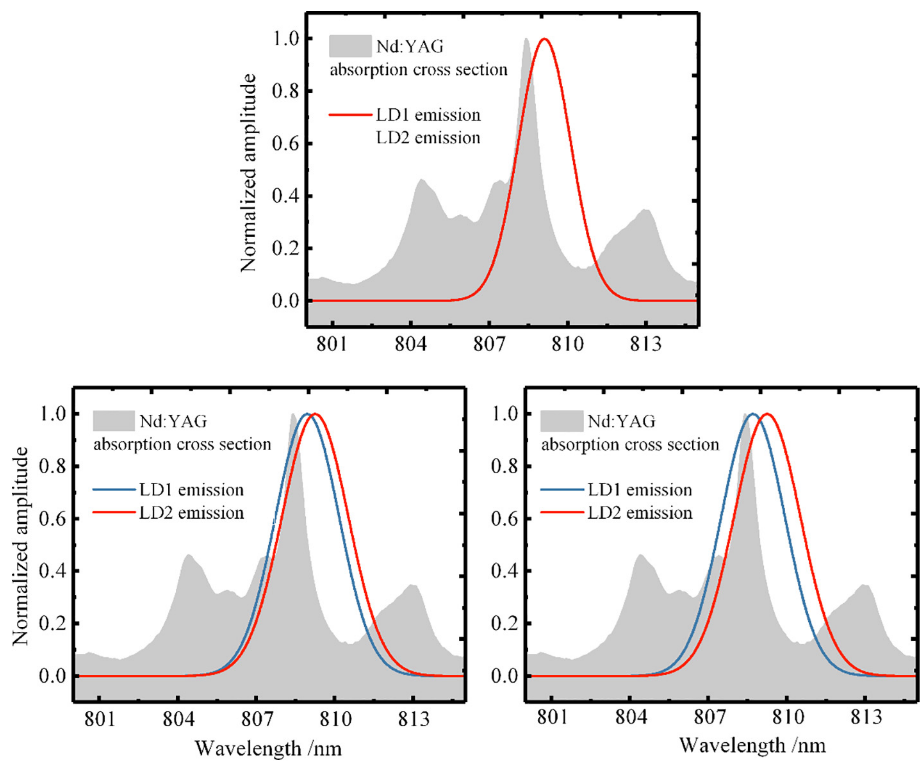

Fig. 3. The spectrum overlap between Nd:YAG absorption spectrum (gray shadow) and LDAs emission spectrum (colored line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

working under repetition rate of 200 Hz. A concave mirror (HR@1064 nm) and a plane mirror (transmission of 20% @1064 nm) were used to construct a resonator for energy storing test, as shown in Fig. 4. An energy meter (BDFL500A-BB-50, Ophir) was used to test the output power.

In some compact package slab laser amplifier modules, the two LDAs cooling water pipes could be connected in series (as shown in Fig. 4(a).) rather than in parallel (as shown in Fig. 4(b).). In our experiment, the cooling water pipe of two LDAs were connected in series. The input cooling water temperature could be adjusted from 22 to 28 °C. The maximum cooling water flow rate was 23 L/min. Two temperature monitors were used to observe the input and output cooling water temperatures. With maximum cooling water flow rate of 23 L/min and under the pump current of 120 A, the temperature difference of input and output cooling water of LDAs was measured to be almost zero. But with cooling water flow rate of 18 L/min, the temperature difference between first and second LDAs pump could be as much as 2 K.

Result and discussion

Under the condition that cooling water pipes were in series connected and pump current was 120 A, the energy storing of the slab module was tested with changing the input cooling water temperature. The experiment and simulation results were shown in Fig. 5. For comparison, both experiment results and simulation results were normalized (dt in simulation is the input cooling water temperature difference between two LDAs). The simulations under

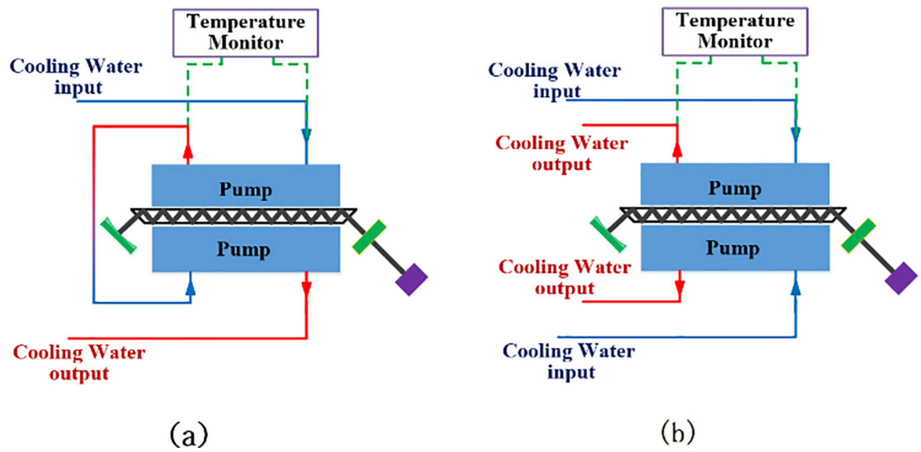

Fig. 4. Experiment setups with cooling water (a) series and (b) parallel connected (blue line indicate the LDAs cooling water input and red line indicates output). Two cavity mirrors were used to test the energy storage of the module. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

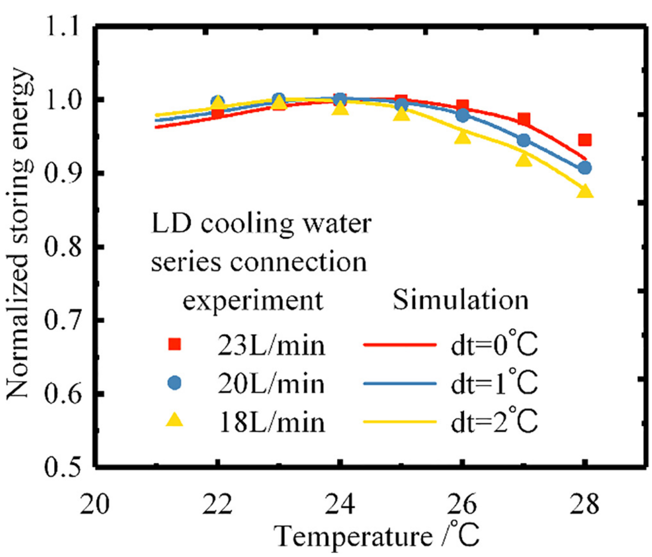

Fig. 5. The experiment and simulation energy storing results (normalized), under the condition that cooling water pipes were in series connected and pump current was 120 A.

different input cooling water temperatures correspond to experiments under different water flow rates.

With cooling water in series connected and under three different cooling water flow rates of 23, 20 and 18 L/min, the energy storing was tested with changing the input water temperature (shown as red square, blue round dot, and yellow triangle dot). The simulations were conducted with two LDAs water temperature differences of 0, 1 K and 2 K (colored line).

Note that all these three series of experiment result were obtained under the condition that the cooling water was in series connected. With cooling water flow rate of 23 L/min, the cooling water temperature difference of two LDAs was pretty small, the experiment result was close to the simulation result that $dt = 0$. Only small difference could be observed when cooling water temperature was high (28–29 °C).

The optimized cooling water input temperatures were obtained by experiment and simulation. In experiment, the optimized temperatures were 23 °C(23 L/min), 23 °C(20 L/min), and 22 °C(18 L/min), respectively. In simulation, the optimized temperatures were 25 °C($dt = 0$ °C), 24 °C($dt = 1$ °C), and 23 °C($dt = 2$ °C), respectively. The difference between experiments and simulations may be due to several reasons, 1) the resolution of the temperature monitors used in experiment was 1 °C, which would fail to identify temperature difference less than 0.5 °C, so the simulation condition may not be exactly the same with the experiment. 2) the LDAs output power may have some fluctuations during the experiment period. These reasons may lead to the difference between experiments and simulations. Also, the power variation near 24 °Cwas quite small. In experiment, when the input water temperature varied from 23 °C to 24 °C, and with water flow rate of 23 L/min, the power decreasing was quite small, only 0.14%(486.2 W to 485.5 W), while the varying from 23 °C to 25 °C, the power decreasing was 0.82% (486.2 W to 482.2 W).

The power decline due to the input cooling water temperature rising was also obtained. In experiment, under cooling water of 28 °C and different water flow rates, the output power decline compared to the maximum output power were 9.46% (486.2 W to 440.2 W, 23 L/min), 14.33%(486.4 W to 416.7, 20 L/min) and 16.94%(483.4 W to 401.5 W, 18 L/min), respectively. With decreasing the cooling water flow rates, the output power declines were increasing. The simulated power decline results were 8.01%, 9.85%, and 12.20%, respectively. The simulation results were in good agreements with experiments. In some practical situation, low cooling water flow rate would increase the system stability and reduce the burden of the cooling water systems.

Conclusion

In this paper, Thermal induced efficiency declines due to spectral overlap between high power LDAs pump and laser medium in double face pumped slab laser were discussed theoretically and experimentally. A numerical model was proposed to compute the overlap efficiency between the pump and laser gain medium spectrum with different LDAs cooling conditions. The energy storing results under two LDAs with different input cooling water temperature differences were computed with numerical model, and the experiment results show a good agreement with simulation results. It found that with input cooling water temperature of 28 °C, the storing energy output power was decreased by 9.46%(23 L/min), 14.33%(20 L/min) and 16.94%(18 L/min) compared to the maximums, respectively. The simulation results show good agreement with experiment. This work would be useful for design and optimization of compact high power and high energy Nd:YAG slab laser that uses high power LDAs as pump.

Acknowledgements

This work was supported in part by the National Key Scientific and Research Equipment Development Project of China (No. ZDYZ2013-2), in part by the China Innovative Talent Promotion Plans for Innovation Team in Priority Fields (No.2014RA4051), in part by the National Natural Science Foundation of China (No. 61605214), in part by the Innovation Program of Academy of Opto-Electronics, Chinese Academy of Science (No. Y70B06A13Y), and in part by the International S&T Cooperation Projects (2014DFR50600).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.rinp.2017.11.034.

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