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Diode-End-Pumped Continuous-Wave Nd:YAG Laser at 946 nm of Single-Frequency Operation[1]

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Abstract—We report a diode-end-pumped continuous-wave (CW) Nd:YAG laser at 946 nm of single frequency operation. A ring laser resonator was designed and the output coupler transmission was optimized based on the investigation of the influence of the output coupler transmission on the thermal lens effect induced by energy-transfer upconversion. A maximum output power of 1.5 W CW single-frequency laser at 946 nm was achieved. The stability of the laser output power was better than ±1% in the given four hours.

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1. INTRODUCTION

During the past few years the diode-pumped solid-state laser operating in the 900 nm region has attracted much attention, as it open the way for efficient generation of blue laser by means of frequency-doubling. The blue laser has numerous applications, such as in high-density optical data storage, color displays, medical diagnostics and precision metrology. Especially, continuous-wave (CW) single-frequency lasers are attractive owing to the spectral sensitivity or spatial resolution can be increased in the laser-based applications. Most present work in this field have been concentrated on Nd:YAG because of its good optical quality, high thermal conductivity, and large Stark splitting of the ground state [1–5]. However, efficient lasing on the quasi-three-level transition ($^4F_{3/2}$–$^4I_{9/2}$) at 946 nm is difficult to achieve because of the significant reabsorption loss, the lower stimulated-emission cross section and serious thermal effect. Several methods had been used to improve the laser performance of Nd:YAG at 946 nm, such as optimizing the length of laser crystal [6], using a composited laser rod [5], efficiency cooling schemes [7], diode pumping directly into the emitting level [8], and using ceramic Nd:YAG [9, 10]. Another factor to limit the scaling of the Nd:YAG laser output power at 946 nm is the influence of energy-transfer upconversion (ETU) [11–14]. First, since the ETU reduces the population of the upper laser level, the laser performance is degraded. Second, the presence of ETU will give rise to an extra heat load in the laser crystal, so the thermal effect is much more serious than that of laser crystal without ETU effect. The thermal lens effect is a critical factor for laser resonator design. Therefore, the thermal lens effect induced by ETU needs to be thoroughly understood.

In this paper, based on the measurement of the thermal focal length of laser medium and the investigation of the influence of the output coupler transmission on the thermal lens effect induced by ETU in quasi-three-level Nd:YAG laser, a ring laser resonator was designed and the output coupler transmission was optimized to build the CW Nd:YAG laser at 946 nm of single frequency operation. 1.5 W CW single-frequency laser at 946 nm was obtained.

2. EXPERIMENTAL SETUP AND RESULTS

The experimental setup of diode-end-pumped Nd:YAG ring laser is shown in Fig. 1.

The pump source is a fiber-coupled diode laser with center wavelength of 808 nm and fiber-core diameter of 400 μm. The pump light was focused into the laser crystal with spot size of 220 μm via a telescope system. To overcome the thermal effects caused by the deformation of the Nd:YAG crystal faces, a composite Nd:YAG rod was used. The composite Nd:YAG rod has a diameter of 3 mm and a length of 11 mm, which consists of a 5 mm long, 1 at % Nd-doped part in the middle and two 3 mm long undoped end caps. Both end faces of the Nd:YAG rod were anti-reflection (AR) coated at 946 nm ($R_{946\,nm} < 0.25\%$) and high-transmission (HT) coated at 808 nm ($T_{808\,nm} > 90\%$). The Nd:YAG rod was tightly wrapped with indium foil for reliable heat transfer and mounted in a copper block, which was temperature controlled by home-made temperature controller with the accuracy of ±0.01°C. To reduce the reabsorption loss, the temperature of Nd:YAG rod was controlled at 12°C. The ring resonator was formed by two plane mirrors (M1, M2) and two plano-concave mirrors (M3, M4). M1 and M2 were high-reflection (HR) coated at 946 nm ($R_{946\,nm} > 99.5\%$) and HT coated at 808 and 1064 nm ($T_{808,\,1064\,nm} > 90\%$). M3 was HR coated at 946 nm

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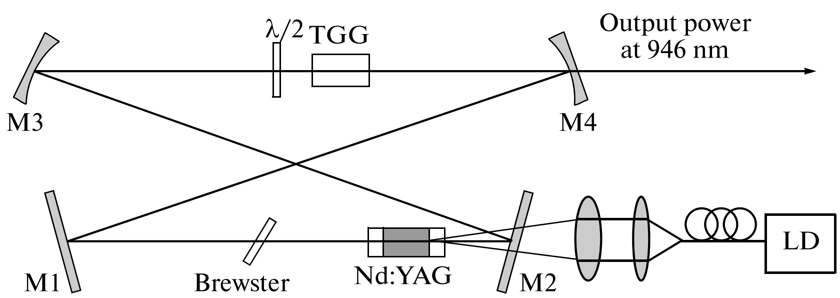

Fig. 1. Experimental setup of diode-end-pumped CW Nd:YAG laser of single frequency operation at 946 nm. LD, laser diode, λ/2, half-wavelength plate.

($R_{946\ \mathrm{nm}} > 99.5\%$) and M4 is an output coupler. The radius of both plano-concave mirrors is 100 mm. Using a Brewster plate and an optical diode formed by a half-wave length plate and a TGG crystal in the resonator, a CW Nd:YAG laser of single frequency operation can be obtained. When the transmission of output coupler is 3.4%, three cases of the cavity length, (1) the optical length between M3 and M4 (L1) is 131 mm and the rest optical length (L2) is 300 mm, (2) L1 = 128 mm and L2 = 280 mm, (3) L1 = 123 mm and L2 = 240 mm, were used to build the CW single frequency Nd:YAG laser at 946 nm. Such kinds of design can make the mode matching between the pump and laser beams and the resonator stable condition to be satisfied when the thermal lens effect of laser crystal is not very serious. The maximum incident pump power is 17, 20, and 25 W in the case of (1), (2), and (3), respectively. When the incident pump power was increased further, the laser oscillation rapidly vanished owing to the more serious thermal lens effect that makes the resonator out of stable region. With the experimental results of the maximum incident pump powers at the different laser cavity lengths, the thermal focal length versus the incident pump power can be calculated by the ABCD matrix formalism with the approximation of a thin thermal lens in the middle of the Nd:YAG crystal, as shown in Fig. 2 (the squares). If we do not consider the ETU effect, the thermal focal length in diode-end-pumped laser can be calculated by [15]

$$f_{\mathrm{th}} = \frac{\pi K_c \omega_p^2}{\xi_0 P_p (dn/dt)[1 - \exp(-\alpha l)]}, \quad (1)$$

where K_c is the thermal conductivity, ω_p is the pump beam radius, P_p is the incident pump power, dn/dt is the thermal-optic coefficient of refractive index, α is the absorption coefficient, l is the laser crystal length, and ξ_0 is the fractional thermal loading. The theoretical prediction is shown in Fig. 2 (the dash line) that is not in agreement with experimental results. So the ETU effect have to be considered and the fractional thermal loading ξ_0 should be substituted by ξ that given by [9]

$$\xi = \xi_0 \frac{N_b}{N_{b\ \mathrm{no\ ETU}}} + 1 - \frac{N_b}{N_{b\ \mathrm{no\ ETU}}}, \quad (2)$$

where N_b and $N_{b\ \mathrm{no\ ETU}}$ are the populations in the upper laser level with and without the ETU effect, respectively. The thermal focal length can be calculated as a function of the incident pump power at output coupler transmission of 3.4% when the ETU effect is considered, as shown in Fig. 2 (the solid line), that obtains good agreement with the experimental results.

It is clear that the maximum incident pump power can be increased when the short cavity length is used that make the resonator in stable region even if the thermal lens effect is more serious. Because the ring resonator is designed to obtain single frequency laser and several optical elements should be inserted into the cavity, we did our best to optimize the cavity length in the experiment and the best result was 240 mm for L2 and 123 mm for L1.

To scale the output power of the CW single frequency Nd:YAG laser, three different transmissions of

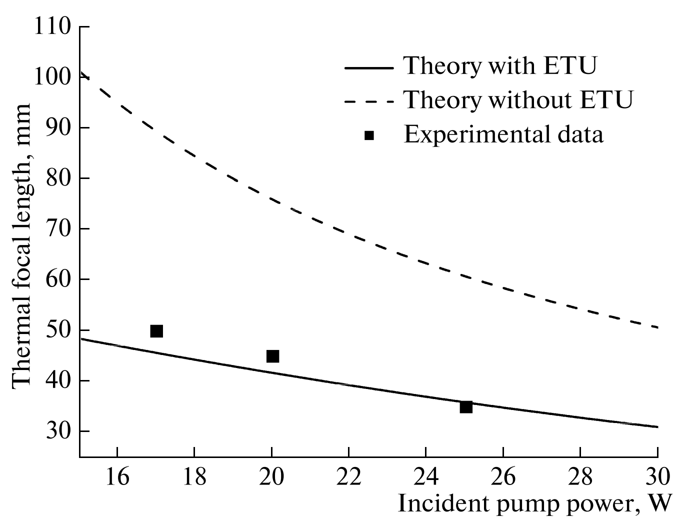

Fig. 2. Thermal focal length versus the maximum incident pump power.

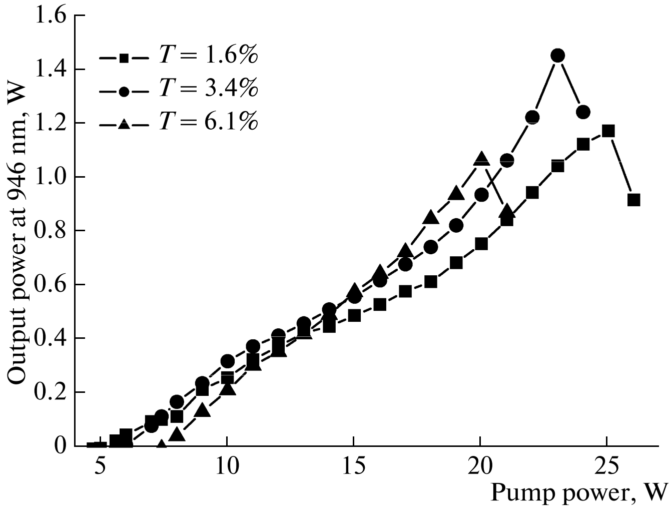

Fig. 3. Laser output power at 946 nm versus the incident pump power at different output coupler transmission.

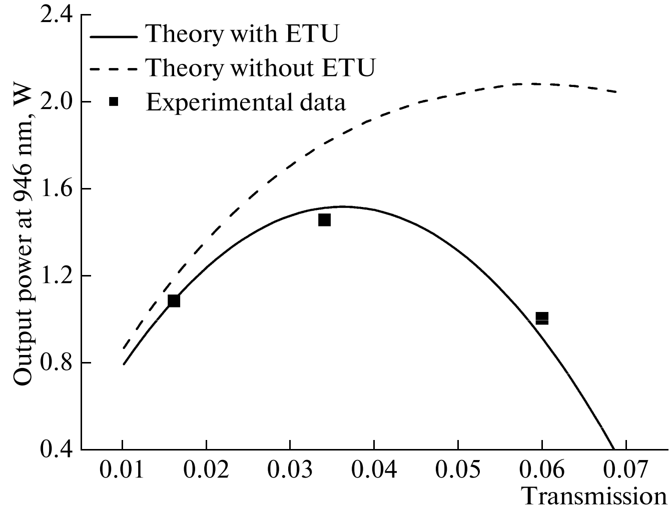

Fig. 4. Relation between the maximum output power at 946 nm and the transmission of output coupler.

the output coupler of 1.6, 3.4, and 6.1% and the optimized cavity length of 240 mm for L2 and 123 mm for L1 were used. The 946 nm laser output power versus the incident pump power is shown in Fig. 3.

The measured maximum output power of 946 nm laser is 1.5 W in the case of transmissions of the output coupler of 3.4%. When the output coupler transmission is increased, the maximum incident pump power is decreased that indicated that the thermal lens effect induced by ETU becomes more serious. When the output coupler transmission is small, more pump power could be incident, but the output power of laser is limited by the low optical conversion efficiency. The relation between the maximum output power at 946 nm and the transmission of output coupler is shown in Fig. 4. The squares are the experimental data. The dash line is the theoretical prediction without the ETU effect. It indicate that if we do not consider the influence of the ETU effect, the optimum transmission of output coupler should be 6% and the maximum output power at 946 nm of 2 W can be obtained at the incident pump power of 32 W. But this theoretical prediction is not in agreement with the experimental results and the influence of the ETU effect has to be considered. The solid line is the theoretical prediction with the ETU effect that obtains good agreement with the experimental results. It can be seen, if the ETU effect is considered, the optimum transmission of output coupler should be 3.6% in the CW Nd:YAG laser at 946 nm of single frequency operation we designed and the maximum output power at 946 nm of 1.5 W can be obtained at the incident pump power of 23 W.

The longitudinal mode of the 946 nm laser was monitored by a scanning confocal Fabry–Perot (F–P) cavity (with free spectral ranges of 750 MHz and fineness of 500) recorded by a digital storage oscilloscope (Agilent Infiniium 54830B). The laser was in single-frequency operation and the frequency shift of the laser output was 30 MHz in 1 min. The measured stability of the 946 nm laser at average output power around 1.4 W is shown in Fig. 5. The stability of the laser output power was better than ±1% and no mode hopping was observed in the given four hours.

3. CONCLUSIONS

We measured the thermal focal length of laser medium firstly and the theoretical prediction with the ETU effect obtains good agreement with the experimental results. Then, the influence of the output cou-

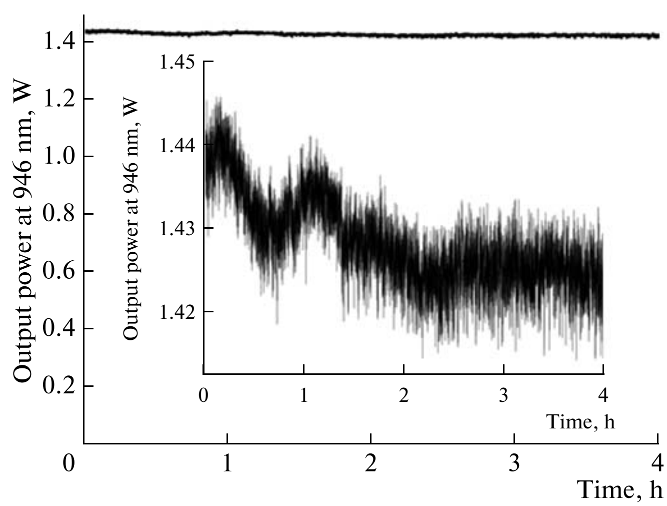

Fig. 5. Measured output power stability of the 946 nm laser at average output power around 1.4 W.

pler transmission on the thermal lens effect induced by ETU in quasi-three-level Nd:YAG laser was investigated. If we consider the influence of the ETU effect, the optimum transmission of output coupler should be 3.6% in the ring Nd:YAG laser we designed. An output power of 1.5 W CW Nd:YAG laser at 946 nm of single frequency operation was obtained. The output power stability of the 946 nm laser was better than ±1% in the given four hours. The stable CW single-frequency laser can be used in the laser-based applications to improve the spectral sensitivity or spatial resolution.

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