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LETTER

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Letter

125 W single-frequency CW Nd:YVO_4 laser based on two-stage dual-end-pumped master-oscillator power amplifiers

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Abstract
We presented a 125 W single-frequency continuous-wave (CW) 1064 nm laser, where a homemade 50.3 W single-frequency CW high quality Nd:YVO_4 laser and a two-stage dual-end-pumped master-oscillator power amplifier (MOPA) acted as the seed source and amplifier, respectively. As a result, a maximum output power of 125.2 W was achieved with the incident pump power of 200 W. The optical-to-optical conversion efficiency and the overall amplified power gain were 43.3% and 3.28%, respectively. The measured beam quality M^2 and the long-term power stability of the 1064 nm amplifier during 8 h were better than 1.28 and ±0.73%, respectively. Additionally, the power extraction efficiency of the designed MOPA system was further investigated and the results revealed that the key of improvement of the power extraction efficiency of the MOPA system was employing a high-power single-frequency CW laser as the master oscillator.

Keywords: master-oscillator power amplifier (MOPA), single-frequency, dual-end-pumped

(Some figures may appear in colour only in the online journal)

1. Introduction

All-solid-state continuous-wave (CW) single-frequency laser has become an important light source in the fields of non-classical optical fields [1], cold atom physics [2], high-precision measurements [3, 4] owing to its intrinsic advantages including perfect beam quality, low intensity noise and high stability. Especially in equipment of the weak signal measurement represented by earth-based gravitational wave detectors which were Michelson-type interferometer, a key factor for the detection sensitivity improvement was to increase the power of the light source because the detector sensitivity was inversely proportional to the square root of the laser power [5]. The advent of the laser amplification technology opportunely paved the way for further scaling up the power of the single-frequency laser. To date, there were two kinds of laser amplifiers including master-oscillator power amplifier (MOPA) [6] and injection-locked amplifier [7]. Compared to the injection-locked amplifier, the MOPA was popular candidate and widely considered as the compact and effective system because the output power of the master oscillator was directly amplified with passing the signal beam through multiple end-pumped [8, 9] or side-pumped laser crystals [10]. According to the types of the laser media, the amplifiers can also be classified into fiber amplifier [11], slab amplifier [12], thin-disk amplifier [13] and solid-state amplifier [14]. In contrast to other amplifiers, it was the easiest to achieve low intensity noise, perfect beam quality and high stability for the solid-state amplifiers, while the power of the master oscillator was scaling up. However, it was noticed that unlike fiber amplifiers, solid-state laser amplifiers had larger mode sizes and hence more seed power was needed to make the MOPA operate in a saturation regime. In 2006, Kim *et al* reported a single-frequency CW Nd:YVO_4 MOPA [15]. Though the number of the used end-pumped laser amplifying crystals were up-to six in their experiment, the output power was restricted to 79 W because the seed power was only 3.8 W. In 2007, Frede *et al* realized a fundamental mode, single-frequency amplifier with output power of 35 W which was constructed by a NPRO seed laser with the power of 2 W and four-stage Nd:YVO_4 amplifier [16]. The power of the designed amplifier was also further scaled up to 65 W by using a seed source with output power of 18 W instead of the previous NPRO. In 2012, Basu *et al* presented a high power single-frequency CW MOPA with the output power of 177 W, which was attained by pre-amplifying the power of NPRO seed laser from 2 W to 72 W by means of employing six end-pumped laser crystals [17]. Moreover, because the gain media of the seed source was different from that of the pre-amplifiers and main amplifiers, they had to precisely match the gain peak by tuning the temperature of the laser media. From the previous researches, it was clear that the power increase of single-frequency MOPA depended on not only increasing the amplifier stages but also scaling up the power of the seed source as far as possible. Additionally, only increasing the amplifier stages directly complicated the laser system and restricted its conversion efficiency as well as stability. In order to break through the restriction of the low power of the seed source, our group designed and achieved a high power single-frequency CW laser with the output power over 50.3 W [18, 19]. On the basis, we constructed a compact MOPA to further scale up the optical power of the single-frequency CW laser. The MOPA was achieved and a compact single-frequency CW 1064 nm laser with output power up to 125 W was obtained.

2. Experimental setup

A two-stage dual-end-pumped MOPA was designed and the schematic diagram was shown in figure 1. The master oscillator was a homemade all-solid-state single-frequency CW Nd:YVO_4 laser with the output power of 50.3 W [18]. The measured beam quality and the degree of polarization were better than 1.1 and 110:1, respectively. A Faraday isolator (IO-5-1064-VHP, Thorlabs) was placed between the master oscillator and the amplifier for preventing parasitic lasing and unwanted feedback to the oscillator. A power adjuster composed of a half-wave plate and a polarization beam splitter (PBS) was utilized to adjust the incident seed power. After the Faraday isolator and the power adjuster, the signal light leaked from the master oscillator was reshaped by f_2 and f_3 with the focal lengths of 200 mm (f_2) and100 mm (f_3) respectively and then injected into the designed two-stage dual-end-pumped MOPA. The core of the designed two-stage MOPA was two a-cut composite YVO_4/Nd:YVO_4/YVO_4 laser crystals with the size of 3 mm × 3 mm × (3 + 19 + 3) mm and the doping concentration of 0.2 at.% for the doped part, respectively. Two un-doped end caps of 3 mm at both ends of the laser crystals acted as the heat sink to reduce the maximal temperature and surface stresses. Both faces of two laser crystals were coated with the anti-reflection films at 1064 and 808 nm. In order to attain the heat dissipation as soon as possible and effectively cooling the temperature of two laser crystals, they were directly mounted in a copper stove full of cooled water. Though the thermal conductivity and mechanical hardness of the Nd:YVO_4 crystal were both lower than that of the Nd:YAG crystal, we still employed the Nd:YVO_4 material as the MOPA laser crystals because of its intrinsic advantages including large stimulated emission cross section and natural birefringence [20]. Moreover, because the Nd:YVO_4 crystal material of the master oscillator was identical to that of the MOPA, it was easy to realize the gain match between the master oscillator and MOPA and therefore achieve an efficient power amplification [21]. Each Nd:YVO_4 crystal was dual-end-pumped with two identical fiber-coupled laser diodes (LD) with pump wavelength at 808 nm and pump power of 50 W (LIMO Co., Ltd). The diameter and the numerical aperture (NA) of every adopted LD were 400 μm and 0.22, respectively. In order to realize a good overlap between the pump light and the signal beam on the amplified laser crystal. The beam waist radius of the signal laser was reshaped to 450 μm at the place of the Nd:YVO_4 laser crystal, and the pump light was focused for a beam radius of 650 μm for optimal mode-matching. With the aid of the dichroic 45° mirrors (S_4–S_7) coated with high reflection (HR, $R > 99.7\%$) at 1064 nm and high transmission (HT, $t > 95\%$) at 808 nm, it was easy to separate the pump lasers from the amplified lasers in the experiment.

3. Experimental results

After two-state dual-end-pumped MOPA was designed, the output characteristics were recorded and compared to that of the four-stage single-end-pumped MOPA reported in our previous research [18]. Figure 2 recorded the output power of MOPA as the function of the incident pump power. It can be seen that maximum output powers of 125.2 ± 1.3 W was realized under the incident signal pump power of 38.6 W and 200 W, respectively, for the two-stage dual-end-pumped MOPA, which was higher than that of 104.1 ± 1.0 W for the four-stage single-end-pumped MOPA. The corresponding optical-to-optical conversion efficiency of 43.3% for two-stage dual-end-pumped MOPA was also higher than that of 32.7% for four-stage single-end-pumped MOPA. In addition, the beam quality of the two amplification setups were measured by a M^2 meter (M2SET-VIS, Thorlabs), which were corresponding to pictures of (a) and (b) shown in figure 3, respectively. It can be seen that the measured values of M_x^2 and M_y^2 for the two-stage dual-end-pumped MOPA were 1.27 and 1.28, respectively, and better than that of 1.35 and 1.38 of the four-stage single-end-pumped MOPA. By the comparison, we can clearly conclude that the maximal output power, the optical efficiency as well as the output beam quality of the two-stage dual-end-pumped MOPA were better than those of the four-stage

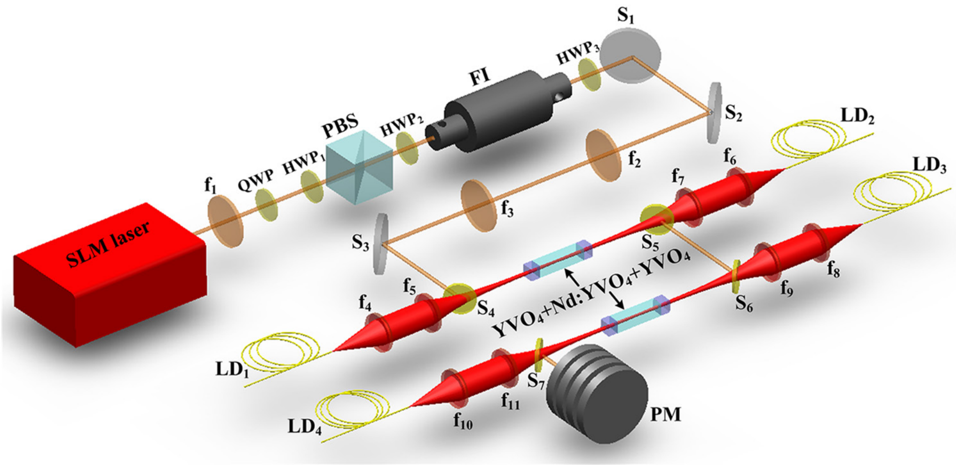

Figure 1. Experimental setup of the dual-end-pumped two-stage MOPA. SLM laser, singlelongitudinal mode laser; QWP, quarter-wave plate; HWP, half-wave plate; PBS, polarization beam splitter; FI, Faraday isolator; S_1–S_3, high reflectivity mirror; S_4–S_7, dichroic mirror; LD_1–LD_4, laser diode; PM, power meter.

single-end-pumped MOPA. The experimental results well revealed that the two-stage dual-end-pumped MOPA scheme can effectively increase the output power, optical conversion efficiency and output beam quality of the amplified 1064 nm laser. The long-term power stability of the two-stage dual-end-pumped MOPA was also measured, and the peak-to-peak power fluctuations at the average output power of 125 W was better than ±0.73% during 8 h, as shown in figure 4. During the data acquisition process, the longitudinal mode structure of the amplified output laser was continuously monitored by a scanned Fabry–Perot cavity with the free spectrum and finesse of 750 MHz and 200, respectively. The measured results illustrated in figure 5 confirmed that the amplified laser worked with single-longitudinal mode operation.

At last, we further investigate the influence of the power of the master oscillator on the power scalability of the designed MOPA. It was well known that the gain of the amplifier can be described as [22]

$$G = \frac{P_{out}}{P_{seed}} = \frac{I_{sat}}{I_{in}} \ln\left\{1 + G_0\left[\exp\left(\frac{I_{in}}{I_{sat}}\right) - 1\right]\right\}, \quad (1)$$

where I_{in} was the power intensity of signal laser, I_{sat} was the saturation intensity, which can be given by $I_{sat} = h\nu/\sigma\tau_f$, where h and ν were the Planck constant and the laser frequency, respectively, and $h\nu$ was the photon energy, σ was the emission cross section, and τ_f was the fluorescence lifetime. G_0 was the single-pass small signal gain, which can be given as: $G_0 = \exp(g_0 l)$, where g_0 and l were the small signal gain coefficient and the length of the laser crystal, respectively.

In order to accurately calculate the power gain of the laser amplifier, the impact of ETU process had been considered in the calculations of the small signal gain coefficient, where g_0 can be obtained by solving the rate equation for the upper level [23]

$$g_0 = \frac{\sigma}{2\gamma}\left\{-\left(\frac{1}{\tau_{sp}} + \frac{1}{\tau_{nr}}\right) + \left[\left(\frac{1}{\tau_{sp}} + \frac{1}{\tau_{nr}}\right)^2 + 4\gamma R_p\right]^{1/2}\right\}, \quad (2)$$

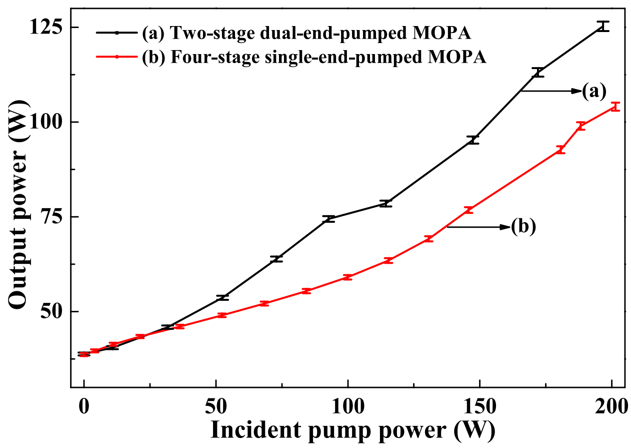

Figure 2. The output power of two-stage dual-end-pumped MOPA (a) and output power of four-stage single-end-pumped MOPA (b) as the function of the incident pump power.

where γ was the upconversion coefficient, R_p was the pumping rate defined as the number of absorbed pump photons per unit of time and volume, τ_{sp} and τ_{nr} were the radiative lifetime and the non-radiative lifetime, respectively. It should be noted that both γ and τ_{nr} were the function of doping concentration [24, 25].

According to the power gain equation of (1) and (2), the amplified output power and power gain as a function of the input seed power were numerical calculated, the corresponding numerical results were shown as square points and circular points in figure 6, respectively. In the experiment, the amplified output power and power gain versus the input seed power varying from 2 W up to 38.6 W were also recorded at the full pump power of 200 W, which were respected to the red curve and blue curve shown in figure 6, respectively. It was clear that under the input seed power of 38.6 W, the measured power gain at the maximum output of 125.2 W was 3.24, which were agreement with the numerical calculations respectively for output power and power gain of 130.1 W and 3.37 under the same condition. In addition, the measured output power

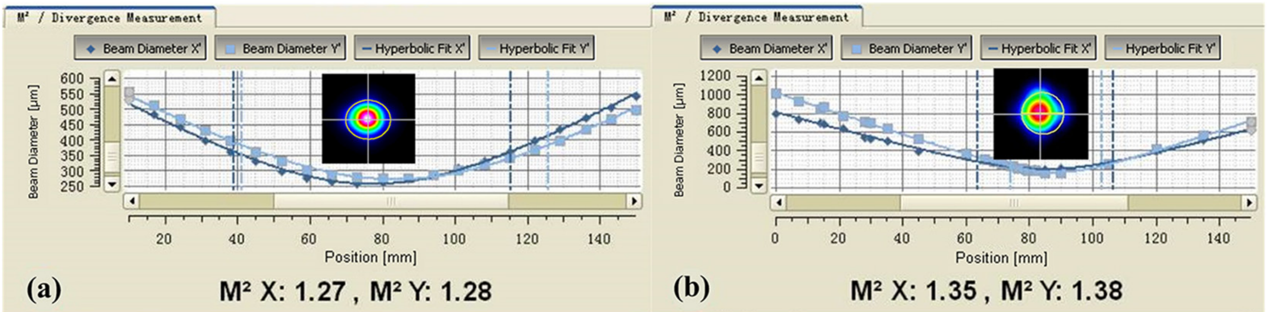

Figure 3. Measured beam quality of the two-stage dual-end-pumped MOPA (a) and the four-stage single-end-pumped MOPA (b).

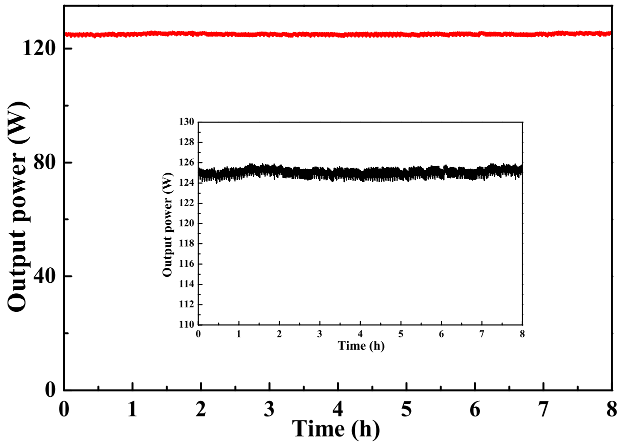

Figure 4. Measured long-term power stability of the amplifier for 8 h at an output power of 125 W.

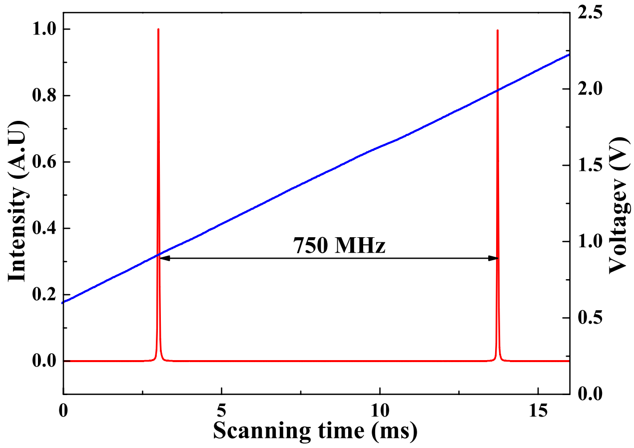

Figure 5. Measured longitudinal-mode structure of the master oscillator laser by scanning the confocal *F–P* cavity.

and the power gain versus the input seed power also basically matched with the numerical calculation results. Therefore, we can obtain that the experimental results showed good agreement with the numerical calculations. Furthermore, the unsaturated power gain of the implemented laser system at the maximal output power revealed that further power scaling can be realized with additional amplifier block. Figure 7 showed the extraction efficiency of the two-stage dual-end-pumped MOPA as a function of the input seed power. Therein, black circular points and the red curve were the measured results and the numerical calculations, respectively. It was clear that

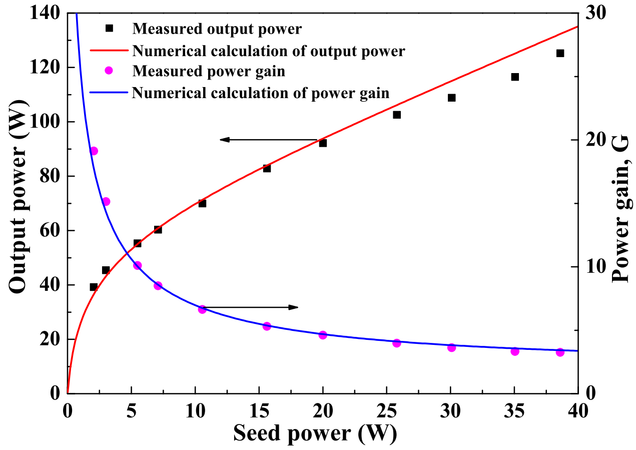

Figure 6. Output power and power gain versus the incident seed power both for experiment results and numerical calculations for the two-stage dual-end-pumped MOPA system.

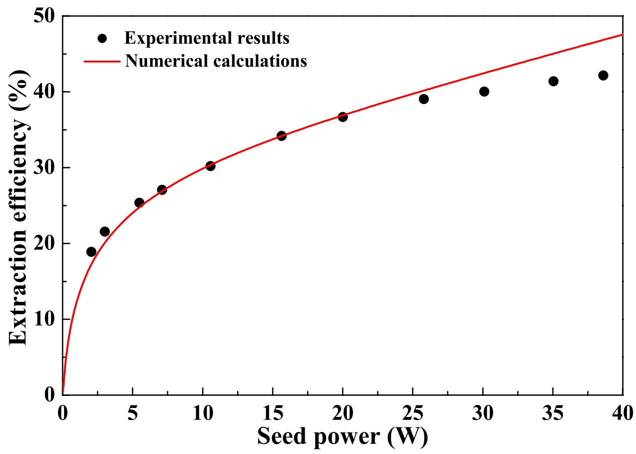

Figure 7. Power extraction efficiency from the two-stage dual-end-pumped MOPA as the function of the incident seed power.

both the measured results and the numerical calculations of the extraction efficiency increased with the increasing of the input seed power, verifying the truth that a high power level of the master oscillator can significantly improve the power extraction from the main amplifier block. Moreover, the measured results of the extraction efficiency of the amplifier were also well consisted with the numerical calculations. Even by comparing the output performance of the designed two-stage dual-end-pumped MOPA system to that of a multi-stage MOPA system with a low power seed laser [14], it definitely revealed that a high-level power master oscillator combined with our amplification scheme can not only reduce the amplifier stage and improve the beam quality, but also increase the output power and power extraction efficiency simultaneously.

4. Conclusion

In summary, we implemented a 125.2 W single-frequency CW $Nd:YVO_4$ laser, where a homemade single-frequency CW high quality 1064 nm laser with power of up-to 50.3 W and an two-stage dual-end-pumped MOPA acted as the seed source and amplifier, respectively. The optical-to-optical extraction efficiency and the overall amplified power gain were 43.3% and 3.24, respectively. The beam quality M^2 and the long-term power stability of the 1064 nm amplifier during 8 h were better than 1.28 and ±0.73%, respectively. The power scalability of the designed MOPA was also numerically calculated and experimentally measured. It was definitely revealed that increase of the injected seed laser power can significantly enhance the power extraction efficiency of the MOPA. The presented work in this paper can provide a good reference for fabricating compact high power, high efficiency CW single frequency lasers with good beam quality.

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