

Research Article

Microchip Nd:YAG and Nd:YVO₄ Lasers Pumped by VHG Wavelength-Stabilized Laser Diode

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We adopted a single-mode, single-wavelength volume holographic grating (VHG) wavelength-stabilized wavelength laser diode (LD) as a pumping LD for an end-pumped microchip Nd:YAG and Nd:YVO₄ lasers we developed during CW and pulse operations. Higher optical-optical and slope efficiencies during CW operation have been obtained than when using a VHG LD experimentally. Output laser power is insensitive to the temperature of the LD when using a wavelength-stabilized LD and can remain stable and almost constant until the temperature of LD increases up to 40°C. The improved optical-optical conversion efficiency of 58% for the Nd:YVO₄ laser has been obtained and calculated the output laser power during CW operation and compared it with the experimental results. We found that the output laser power of the Nd:YVO₄ laser using the VHG wavelength-stabilized LD was more than twice as high as that using an LD without VHG. When the ambient temperature increases, the difference in output laser power should be large. In the future, a low-cost end-pumped microchip laser that does not require a temperature control should be developed.

1. Introduction

Solid-state lasers are compact and efficient and have high beam quality, and the application of laser diode- (LD-) pumped lasers to the industrial field has expanded. Various end-pump microchip solid-state lasers under CW and pulse operations have been developed [1–16]. Current Nd:YAG/Cr:YAG microchip lasers realize over 1 mJ with over 1 MW of peak power [4]. A microchip solid-state laser can generate a high gain with low loss in a small volume, can easily obtain high beam quality and a short pulse, and is compact, comparable to an LD. Direct processing using an LD is possible; however, an LD is extremely difficult to operate with a pulse duration in ns because this would limit the lifetime of an LD module. End-pumped microchip lasers can easily generate ns-laser pulses with high peak power. Neodymium-doped yttrium aluminum garnet (Nd:YAG) crystals have been used as laser media for microchip lasers; however, the absorption bandwidth for the pump light is as

narrow as 2.5 nm [17], and when the temperature of the LD increases, the peak wavelength of the output light shifts to the longer wavelength side, so LD temperature should be controlled. Thus, the cost of laser systems increases.

The possibility of a laser using a neodymium-doped yttrium orthovanadate (Nd:YVO₄) crystal was reported in 1966 [2]. An Nd:YVO₄ crystal has a stimulated emission cross section, which is three times higher than that of an Nd:YAG crystal, and has a seven times higher absorption coefficient at π -polarization. Higher laser power can be achieved with an Nd:YVO₄ crystal during CW operation than with an Nd:YAG crystal. However, the laser output fluctuates due to the difference in absorbed power of the pump light at low and high temperatures due to the shift in the peak wavelength of the LD, which is not the case when using an Nd:YAG crystal.

Research has been conducted to stabilize the output frequency by using the feedback of the partial output light of an LD to semiconductors [18, 19]. We developed an end-

pumped Nd:YVO₄ laser that uses a volume holographic grating (VHG) wavelength-stabilized narrow band LD for pumping. The narrowband LD is important for laser systems because it increases the amount of absorbed light and fixes the central peak wavelength for the LD temperature. Previous studies have reported on Tm:YAG and Yb:YAG lasers pumped using a VHG-stabilized narrow band LD [20, 21], and experiments for generating repetitive pulses by Q-switching and during CW operation were conducted. Output laser power was compared with that using a conventional LD without VHG. The temporal stability of the output laser power was also investigated.

2. Calculation of Output Laser Power

The CW output laser power for a microchip laser is calculated as follows [22]:

$$P_{\text{out}} = \left[\frac{g_0}{L} - 1 \right] \cdot \frac{T}{L} \cdot P_{\text{sat}} \cdot A, \quad (1)$$

where A_s is the effective pumping cross section, L is the loss of light in the laser cavity, T is $1 - R_2$, where R_2 is the reflectivity of the output mirror, P_{sat} is the total fluorescence power in the laser cavity, and A is the coupling ratio of the initial fluorescence to the cavity. The large gain G , small signal gain coefficient $g_0 l$, and inversion population of the laser medium N_{inv} are calculated as

$$G = \exp(g_0 l) = \exp(\sigma_L N_{\text{inv}}), \quad (2)$$

$$N_{\text{inv}} = \Delta N \cdot \tau_R,$$

where ΔN is the pump rate per unit volume and τ_R is the fluorescence lifetime of the laser medium. The population density of Nd ions at the lower level for Nd:YAG and Nd:YVO₄ is omitted because the temperatures of the laser materials are below 40°C. The ΔN is calculated as

$$\Delta N = \frac{\eta_q \cdot \eta_a \cdot P_{\text{in}}}{A_s \cdot h(C/\lambda_p)}, \quad (3)$$

where P_{in} is the pump power of the LD light, λ_p is the pump wavelength, η_q is the emission efficiency of the laser material, and η_a is the absorption rate of the pumping light. The average output laser power of a high repetitive pulse laser is calculated as

$$P_{\text{out}} = \Delta E_{\text{out}} f, \quad (4)$$

where ΔP is the energy of the single laser pulse and f is the repetition rate.

The Nd:YAG parameters for calculating the output laser power are described below. We used equations (1)–(3) to calculate the CW output laser power of the Nd:YAG and Nd:YVO₄ lasers. The stimulated emission cross section σ_L of Nd:YAG and Nd:YVO₄ crystals was set to $2.8 \times 10^{-19} \text{ cm}^2$ and $1.6 \times 10^{-18} \text{ cm}^2$, respectively, and τ_R was set to 230 and 100 μs , respectively [17].

The focused spot diameter of LD light on the laser materials was assumed to be 230 μm for an LD without VHG and 160 μm in the case of the VHG LD. Thus, A_s was set to 0.0004 and 0.00020 cm^2 when using the LD without VHG

and VHG LD, respectively. The lengths of the Nd:YAG and Nd:YVO₄ crystal rods were set to 7 and 1 mm, respectively. The optical loss of the laser material at the laser wavelength was ignored because the thickness of the laser materials was thin. The transmittance of the pumping light in the HR coating was set to 100%. The η_q of both laser materials (including optical loss) with respect to the excitation light was set to 90%.

3. Experimental Setup

The experimental setup for the two microchip lasers is shown in Figure 1. The lasers contain either an Nd:YAG crystal (size: 3 mm Φ , 7 mm thick, CASTECH) or Nd:YVO₄ crystal (size: 3 mm Φ , 1 mm thick, a-cut, CASTECH). We used an HR coating of 1064 nm and an AR coating of 809 nm on the pumping sides of the crystals. The other sides had an AR coating of 1064 nm. For the CW laser operation, the cavity length was set to 10 mm, and the reflectivity of the output coupling mirror was 90%. Two types of LDs were used as pumping light sources: an LD without VHG (single-mode one-chip, LD 808-SE500, Thorlabs) and an LD (single-mode one-chip, LD 808-SEV500, Thorlabs) with VHG (hereafter, VHG LD) for partial LD optical feedback to fix the output wavelength. The peak wavelengths of the output light from the two LDs at 25°C were 808.5 and 808.3 nm, respectively. The divergence angles at these peak wavelengths of the output light for the LD without VHG were 14° and 7° and those for the VHG LD was 14° and 8°. The performance of the focused LD light for the VHG LD was better than that of the LD without VHG because the spatial distribution of the LD light for the VHG LD was concentrated at the center. The bandwidth of the emission spectrum at 808 nm was 2.5 nm (full width at half maximum (FWHM)) for the LD without VHG and 0.1 nm (FWHM) for the VHG LD. The amount of spectral peak shift for the VHG LD was 0.1 nm with a temperature increase of 5°C. For the LD without VHG, the amount of peak shift was 1.0 nm with the same temperature increase. Since the VHG LD had a VHG near the semiconductor for returning the output LD light, the spatial pattern of the LD light in the near field was partially missing, but this does not affect the focusing pattern of the microchip laser.

The LD was set tightly in a copper holder. A temperature-control device with a Peltier cooler and electronic controller (TED200C, Thorlabs) was used to control the LD temperature.

A thermistor for the temperature measurement was installed outside the LD can. The output light from the LD entered once through a single lens with AR coating ($f = 6.24 \text{ mm}$) and then collected in front of the laser media. The Nd:YAG crystal was fixed in a heatsink copper folder (14 \times 14 mm², 10 mm) to exhaust the generated heat. The Nd:YVO₄ crystal was fixed on a heatsink copper plate (14 \times 14 mm², 0.5 mm) because of its thinness.

A Cr⁴⁺:YAG crystal with a diameter of 10 mm was set near the laser materials, as shown in Figure 1, for generating repetitive pulses by Q-switching. The initial transmittance of the Cr⁴⁺:YAG crystal was 90%. A bandpass filter at the laser wavelength was used to measure the output laser power, which was normalized.

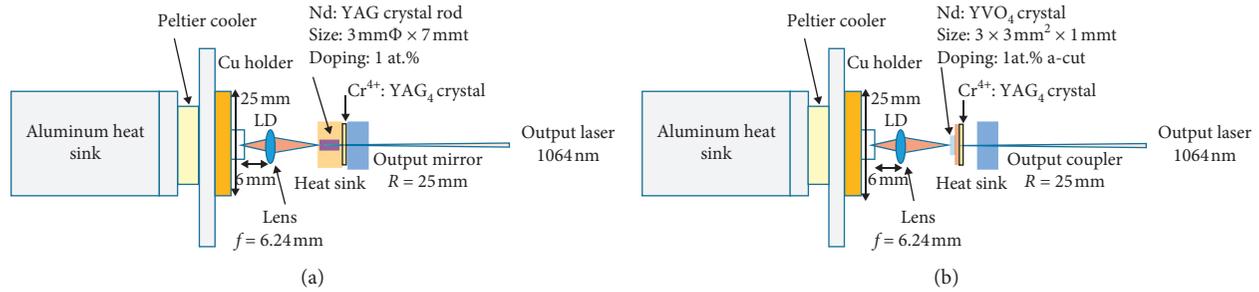


FIGURE 1: Experimental setup for (a) Nd:YAG and (b) Nd:YVO₄ lasers.

4. Experimental Results

The experimental results for generating a CW laser are shown in Figure 2. The dots are the experimental results, and the solid lines are results calculated using equations (1)–(3). The spatial beam profiles of the microchip lasers were quasi-Gaussian. The room temperature was 23°C.

For the Nd:YAG laser using the LD without VHG, the threshold for the pump power was 70 mW, slope efficiency was 40%, and maximum output conversion efficiency was 33%, as shown in Figure 2. The maximum output laser power was 160 mW. Generated heat in the semiconductor chip of a can-type LD cannot be exhausted when the output power of the LD light is high. As the temperature of the LD increases, the peak wavelength of the LD light shifts to the longer wavelength side. Thus, the output of laser power is saturated when the pump power increased to around 400 mW.

In the range of pump power (below 370–380 mW) where the thermal shift of the LD without VHG shows good superposition with the absorption line of Nd, the slope efficiency is higher without LD stabilization. This is because the peak wavelength of the VHG LD light is a little shorter than that of the absorption band for the Nd:YAG. The peak wavelength of the output light for the LD without VHG is almost the same as that of the absorption band for the Nd:YAG.

The threshold was also 60 mW for the Nd:YAG laser using the VHG LD, but the slope efficiency was 43% and maximum output conversion efficiency was 37%. The conversion efficiency and slope efficiency increased slightly. The maximum output laser power was 200 mW.

The peak wavelength of the LD light shifts to the longer side as the temperature of LD increases. Thus, increasing the absorbed power of the LD light resulted in increasing the output laser power slightly and nonlinearly.

For the Nd:YVO₄ laser using LD without VHG, the threshold for the pump power was 20 mW, slope efficiency was 47%, and conversion efficiency at the maximum output was 36%, as shown in Figure 3. The maximum output laser power was 160 mW. For this laser using the VHG LD, the threshold was 10 mW, slope efficiency was 56%, and maximum output conversion efficiency was 54%, as shown in Figure 3. These results indicate that the conversion and slope efficiencies improved using the VHG LD. The obtained maximum output laser power was 290 mW. When the pump power is 600 mW, the output laser power should reach

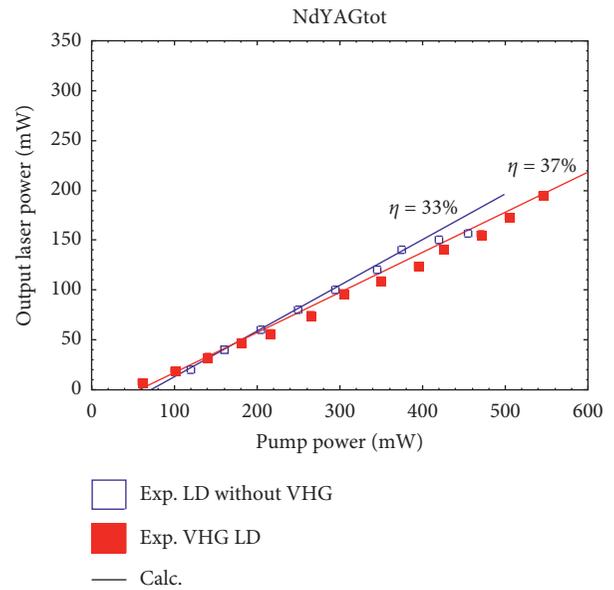


FIGURE 2: Output laser power of Nd:YAG laser during CW operation.

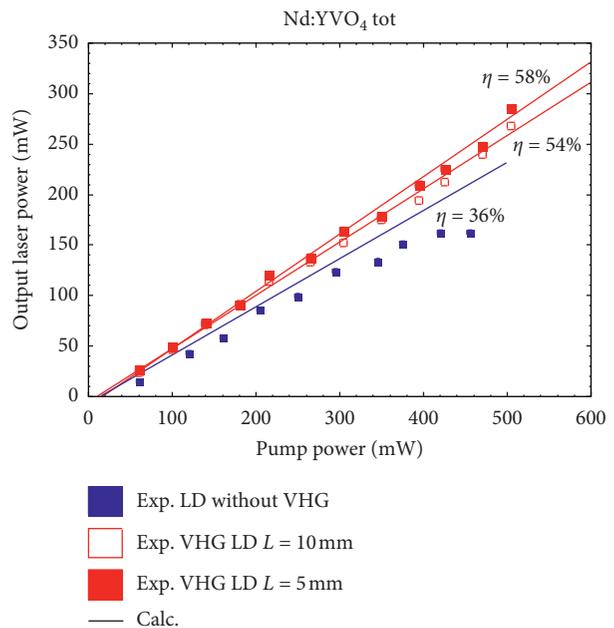


FIGURE 3: Output laser power of Nd:YVO₄ laser during CW operation.

320 mW. The maximum output laser power of the Nd:YVO₄ laser using the VHGLD was twice as high as that of using the LD without VHGLD.

When we changed the resonator length for the Nd:YVO₄ laser using the VGHLD to 5 mm, the threshold was 20 mW, slope efficiency was 59%, and maximum output conversion efficiency was 58%, as shown in Figure 3.

Normally, the output laser power of a four-level laser oscillator (such as the Nd:YAG laser) is calculated to change almost linearly with the pump power. However, when the pumping power was high in the experiment, the temperature of the laser medium increased and the output was saturated. When the pump power was about 500 mW in this experiment, the temperature of the laser medium was low, so the above does not apply. The difference in laser power for $L = 5$ and 10 mm is the use of pumped volume.

The conversion and slope efficiencies increased using the VHGLD, and the obtained maximum output laser power was 290 mW. When using the VHGLD, the threshold decreased by 50%, and the slope efficiency and output power also increased. This is probably because the bandwidth of the output light from the LD narrowed, spatial mode improved, the divergence angle of the LD light decreased, and the focusing diameter of the pumping LD light decreased.

Both LD output power characteristics used in this experiment do not change with an increase in temperature and show only a slight decrease from 25°C to 35°C at the output power of 500 mW. Even if the temperature increases 10°C, the output power will not decrease significantly for the LD current. Exhausting the heat of the LD cannot catch up and the chip temperature increases to around 30°C. The peak wavelength of the LD light shifts to a long wavelength and moves away from the peaks of the absorption band for the Nd:YAG and Nd:YVO₄, so the laser output decreases. When a VHGLD is used, the output power increases linearly with the pump power. This also shows that the pump power does not drop as a function of the LD current.

The calculated results of the optimum coupling reflectivity of the output mirror and conversion efficiency are shown in Figure 4. In this experiment, we set the reflectivity of the output mirror to 90%. We conducted a computer analysis to investigate whether the coupling was optimal. A cavity length of 10 mm and the VHGLD were assumed. The pump power was set to 500 mW and the absorption rate was assumed maintained at 100% up to 35°C. For the Nd:YAG laser, the optimum output mirror reflectivity was 90%. In contrast, it was just 80% for the Nd:YVO₄ laser. The output was 295 mW, and the conversion efficiency of 60% was expected from the calculation results. The output laser power of the Nd:YVO₄ laser was twice as high as that of the Nd:YAG laser.

The experimental results for the stability of laser power with respect to LD temperature are shown in Figure 5, where I is LD current. Temperatures below 23°C could not be set due to the problem of the cooling system. For the Nd:YAG laser using the LD without VHGLD, the output laser power was 45 mW at 24°C, as shown in Figure 5(a), and the pump power was 150 mW. When the temperature increased to

35°C, this power gradually decreased to 19 mW. For this laser using the VHGLD, the output laser power was 12 and 35 mW at 23°C, as shown in Figure 5(a), and the pump power was 100 mW. When the temperature increased to 39°C, this power was kept constant. For the Nd:YVO₄ laser using the LD without VHGLD, the output laser power was 47 mW at 23°C, and the pump power was 72 mW, as shown in Figure 5(b). When the temperature increased to 35°C, this power gradually decreased to 35 mW. For this laser using the VHGLD, the output laser power was 45 mW at 24°C, and the pump power was 150 mW. When the temperature increased to 39°C, this power was kept constant, as shown in Figure 5(b).

The calculated absorption rate of laser materials as a function of the LD temperature obtained from the experimental results is shown in Figure 6. In the case of both Nd:YAG and Nd:YVO₄, the calculated the absorption rate of the absorbed pump power was normalized by the maximum absorbed pump power. For the Nd:YAG laser using the LD without VHGLD, we found that the absorption rate decreased by 30% compared to that at 24°C when the temperature increased to 35°C. For this laser using the VHGLD, when the temperature increased to 35°C, the absorption rate decreased only 5% compared to that at 24°C. For the Nd:YVO₄ laser using the LD without VHGLD, the absorption rate decreased by 20% when the temperature increased to 35°C. For this laser using the VHGLD, the absorption rate did not decrease up to 35°C. The output laser power was maintained owing to the broad effective absorption bandwidth at the pumping wavelengths of the Nd:YAG and Nd:YVO₄ crystals, which are 2.5 and 15.7 nm, respectively [17]. The absorption rate of the pump power for both laser materials could be maintained when the LD temperature increased to 35°C when using the VHGLD.

The calculated results of the g_0l and G in a small signal are shown in Figure 7. We found that Nd:YVO₄ had a gain coefficient 4.7 times higher than that of Nd:YAG. This is presumably because the absorption area of the focused LD light for Nd:YVO₄ was small. The multiplication of σ_L and τ_R resulted in a large difference in the gain coefficient. It is clear that the Nd:YAG and Nd:YVO₄ lasers can maintain G even at an LD temperature of 35°C. Particularly for the Nd:YVO₄ laser, a high G can be maintained using the VHGLD.

In fact, the peak wavelength of the LD light shifts due to increasing the temperature of the LD. However, since the absorption band was wide for the Nd:YVO₄, the output could be maintained against the temperature change of the LD. In addition, the Nd:YAG had a narrow absorption band and thus exhibited a slight decrease in laser output. However, it was shown that the VHGLD is effective for maintaining the output laser power even at high temperatures when using the Nd:YAG.

The experimental results for pulse laser generation are shown in Figure 8. The spatial beam profiles of the microchip lasers were a quasi-Gaussian type.

For the Nd:YAG laser using the LD without VHGLD, the threshold for pumping power was 160 mW, slope efficiency was 18%, and maximum output conversion efficiency was

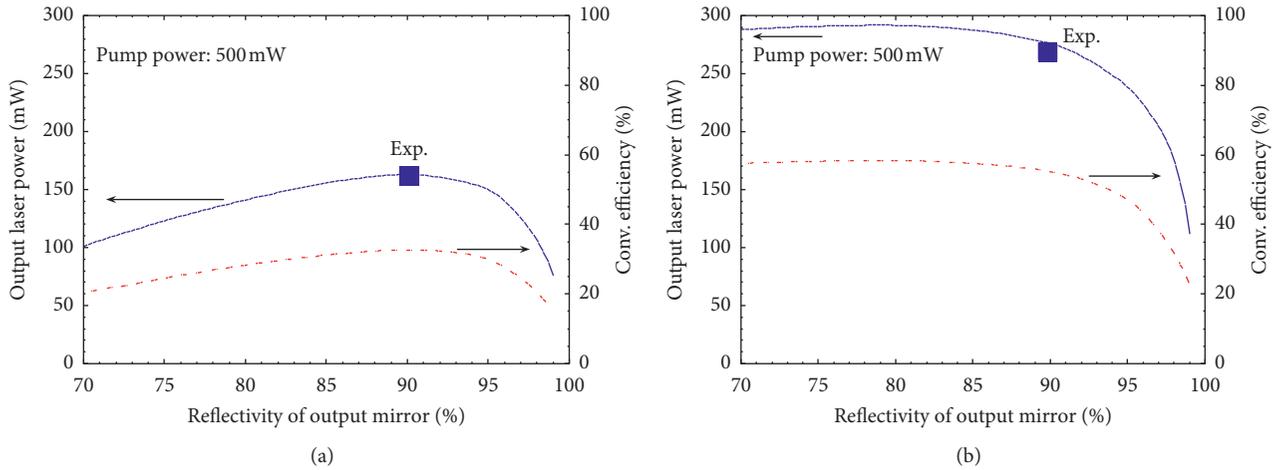


FIGURE 4: Calculated output laser power and conversion efficiency for the reflectivity of output mirror: (a) Nd:YAG and (b) Nd:YVO₄.

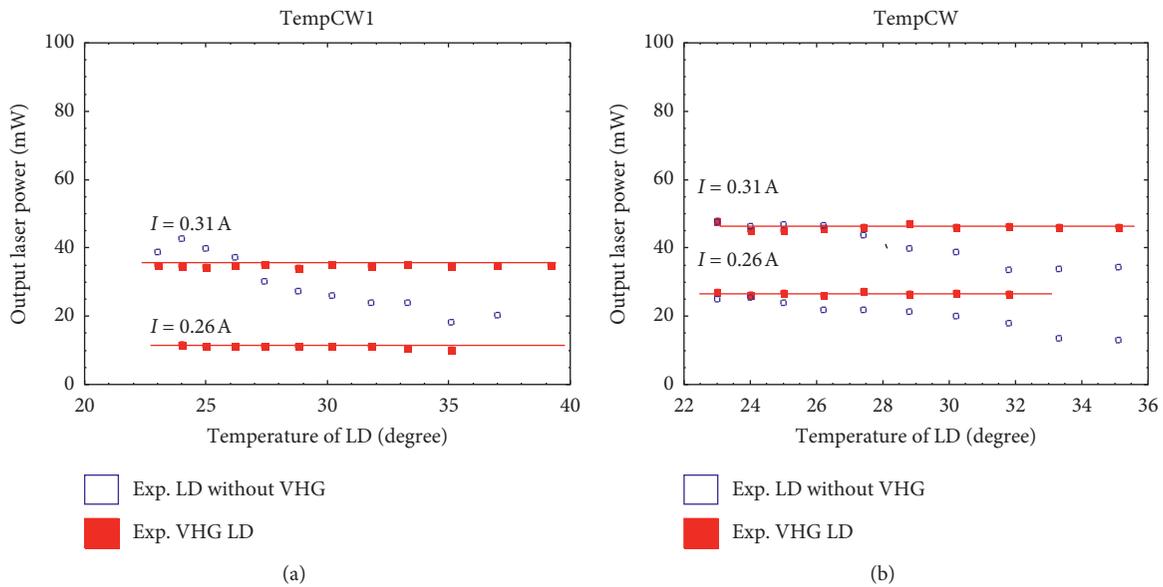


FIGURE 5: Stability of output laser power for LD temperature: (a) Nd:YAG and (b) Nd:YVO₄.

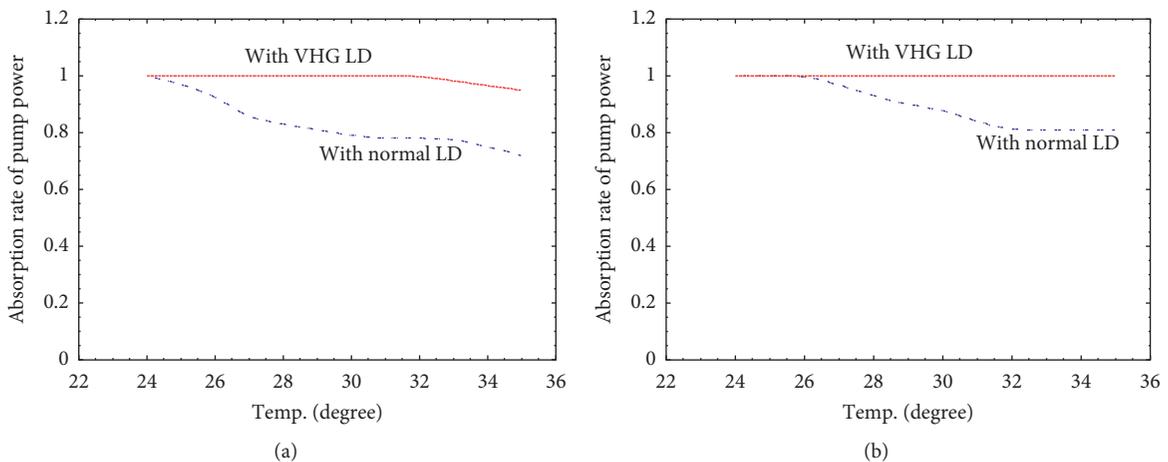


FIGURE 6: Absorption ratio of laser materials as a function of LD temperature: (a) Nd:YAG and (b) Nd:YVO₄.

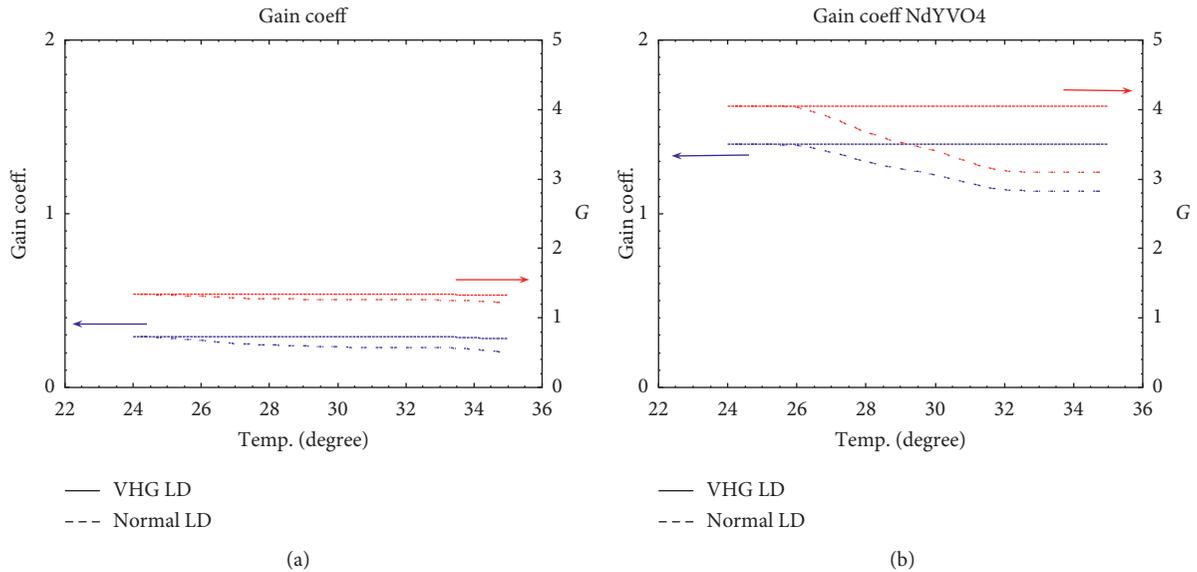


FIGURE 7: Calculated small signal gain coefficient and laser large gain: (a) Nd:YAG and (b) Nd:YVO₄.

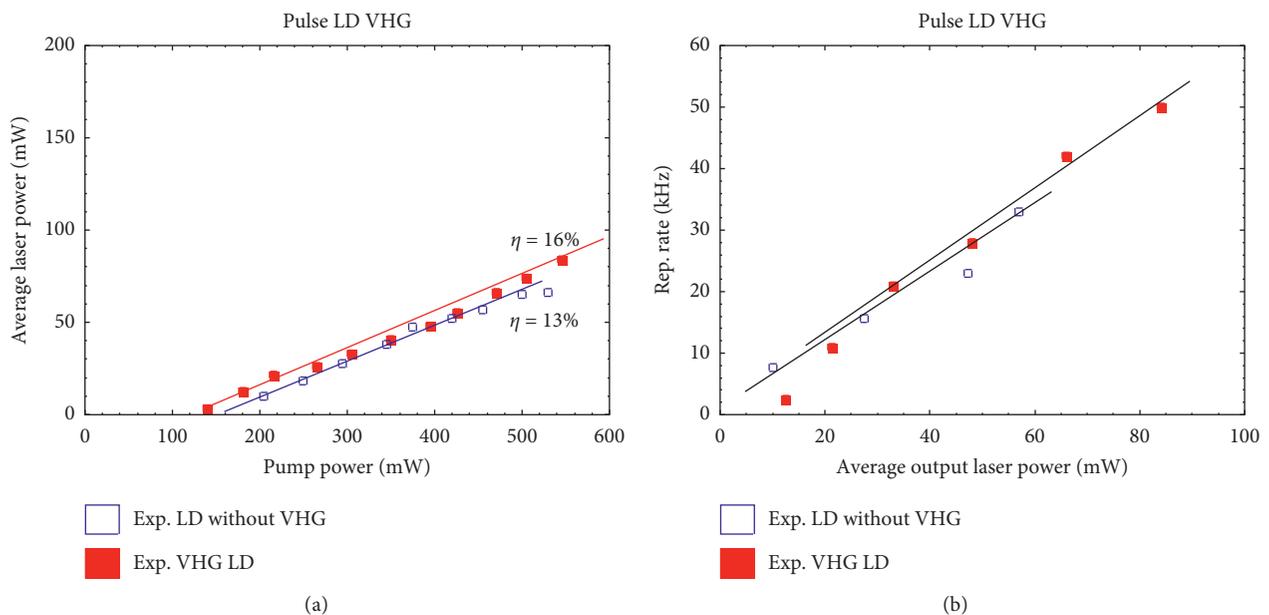


FIGURE 8: Nd:YAG laser under pulse operation: (a) average output laser power and (b) repetition rate.

13%, as shown in Figure 8(a). The threshold was also 140 mW for this laser using the VHG LD, but the slope efficiency was 21% and maximum output conversion efficiency was 16%, as shown in Figure 8(a). The conversion and slope efficiencies increased slightly by using the VHG LD.

The repetition rate varied from 7 to 36 kHz for the Nd:YAG laser using the LD without VHG. It also varied from 2 to 60 kHz when using the VHG LD, as shown in Figure 8(b). The pulse duration of this laser was 8 ns, and the peak power was evaluated to be 225 W.

For the laser using the Nd:YVO₄ laser using the LD without VHG, the threshold for the pump power was 160 mW, slope efficiency was 50%, and conversion efficiency at the maximum output was 30%, as shown in Figure 9(a), and

the maximum output laser power was 135 mW. For this laser using the VHG LD, the threshold was 30 mW, slope efficiency was 36%, and maximum output conversion efficiency was 33%, as shown in Figure 9(a). These results indicate that the conversion and slope efficiencies increased using the VHG LD. The obtained maximum output laser power was 180 mW.

The repetition rate varied from 400 to 800 kHz for the Nd:YVO₄ laser using the LD without VHG. It also varied from 400 to 900 kHz for this laser using the VHG LD, as shown in Figure 9(b). The pulse duration of the laser was 28 ns, and the peak power was evaluated to be 7.1 W.

Experimental results for the stability of the output laser power with respect to LD temperature are shown in Figure 10. For the Nd:YAG laser using the LD without VHG,

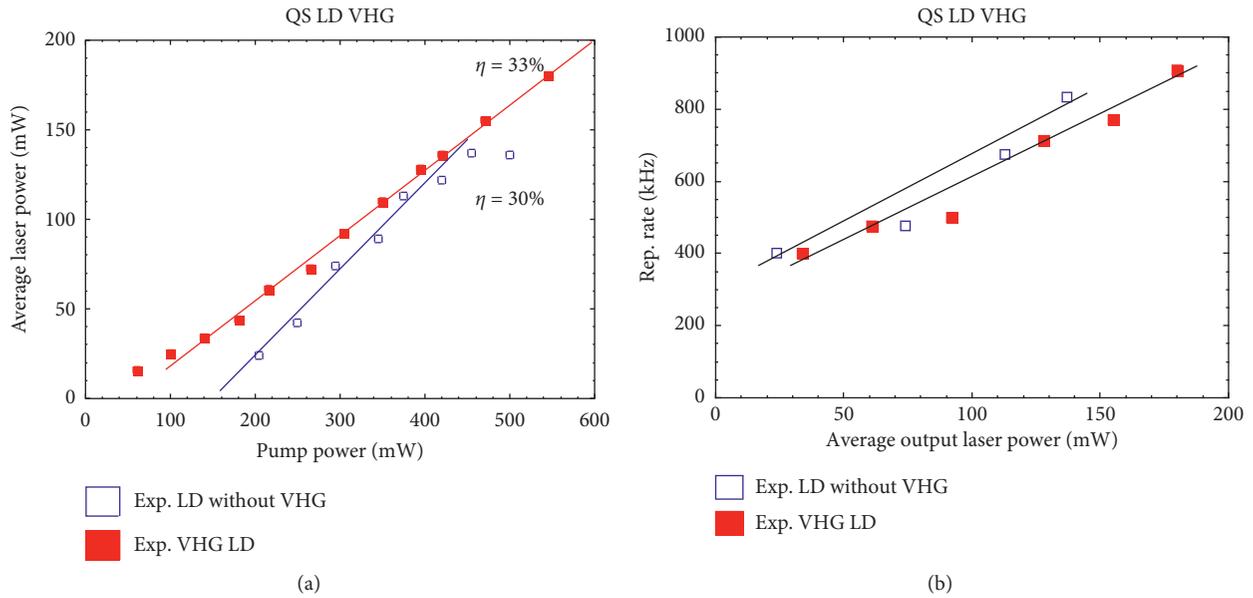


FIGURE 9: Nd:YVO₄ laser under pulse operation: (a) average output laser power and (b) repetition rate.

the average output laser power was 16 mW at 25°C, as shown in Figure 10(a), and the pump power was 200 mW. When the temperature increased to 39°C, this power decreased to 8 mW. For this laser using the VHG LD, the average output laser power was 22 mW at 23°C, as shown in Figure 10(a), and the pump power was 210 mW. When the temperature increased to 39°C, this power was kept constant.

For the Nd:YVO₄ laser using the LD without VHG, the average output laser power was 20 mW at 23°C, and the pump power was 200 mW, as shown in Figure 10(b). The output laser power decreased to 15 mW when the temperature increased to 35°C. For this laser using the VHG LD, the average output laser power was 55 mW at 23°C, and the pump power was 210 mW. When the temperature increased to 35°C, this power was kept constant.

These experimental results indicate that microchip lasers can be driven by simply cooling LDs to a temperature at which the LDs will not be damaged, even without a temperature controller. This enables us to simplify the device. Increasing the pump power of the LD light and obtaining a higher output laser power are for future work.

These microchip lasers are intended for operating up to around 40°C. Because the heat generated in the laser material is below 0.5 W, the temperature of the laser material is 10°C higher than the ambient temperature. Thus, the optical parameters of the laser materials should not change. However, when the output power of the LD light significantly increases, the laser material generates a large amount of heat and the optical parameters change. Thus, cooling the laser material and keeping the temperature constant are necessary.

In the case of CW laser emission, the slope efficiency depends on pump absorption efficiency, quantum efficiency, pump and resonator mode matching, quantum

defect, output mirror transmission, and residual optical loss. In the case of laser materials with high quality, laser material and pump characteristics enable slope efficiency close to the quantum defect by selecting the resonator properly. An experimental result on the conversion efficiency in [3] is close to the quantum defect. However, in that study, the pump wavelengths were slightly longer than 808 nm, which is slightly different from our experimental conditions. They obtained high conversion efficiency is 75%. The maximum conversion efficiency at 808 nm pumping should be evaluated to be 71% considering the emission efficiency of 93% and quantum defect (excitation wavelength versus emission wavelength) of 76%. In that study, CW laser emissions were reported. A short pulse laser was used for pumping with high intensity to increase the laser gain, and the LD output power was modulated by temporally controlling the current to increase pumping peak intensity with reducing thermal load. In experiments, the real emission efficiencies of Nd:YVO₄ and Nd:YAG are evaluated to be 100% [3, 10].

In our study, the intensity of pump light was low, the laser gain was not high as fiber lasers, the ratio of mode utilization was low, the reflectance of the output mirror was high, and the extraction efficiency was low, so the conversion efficiency was limited to 60%. However, the conversion efficiency will be higher than that of the standard Nd:YVO₄ microchip laser [2]. In our experiment, when the current was further controlled temporally and the LD output power was modulated to reduce the heat load, the pumping density increased, the laser gain increased, and the output mirror reflectance decreased. The conversion efficiency should approach 71% under quasi-CW oscillation, and higher output power should be obtained. Also, in pulse mode, conversion efficiency should improve and high peak power should be obtained.

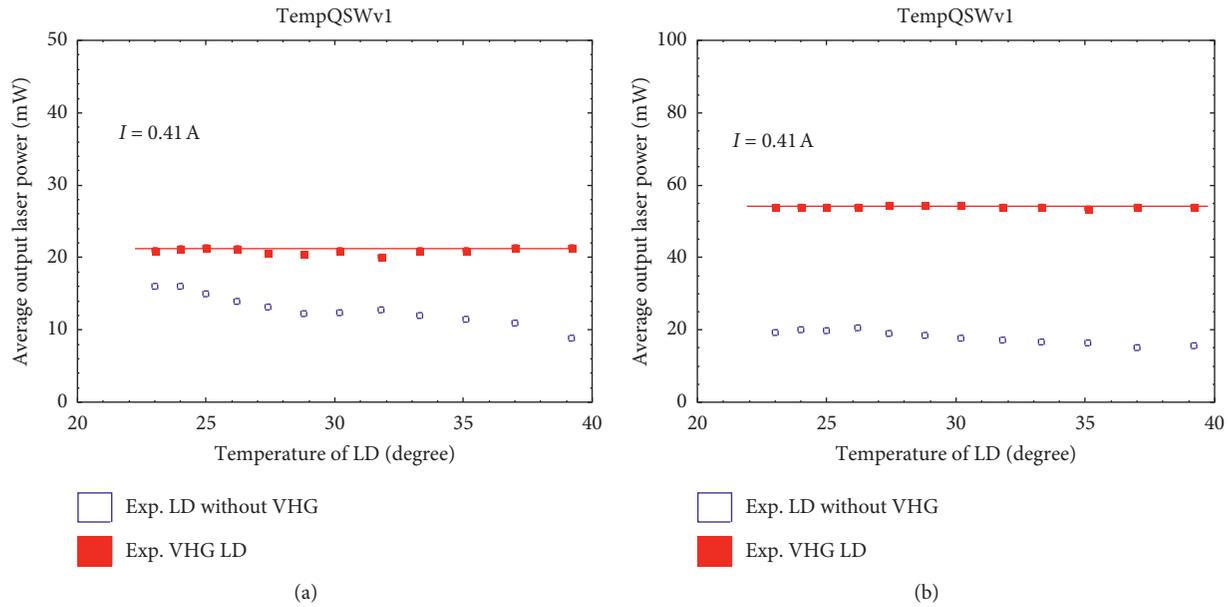


FIGURE 10: Stability of laser power for LD temperature: (a) Nd:YAG and (b) Nd:YVO₄.

5. Conclusion

We developed end-pumped microchip Nd:YAG and Nd:YVO₄ lasers pumped using a VHG LD as a pumping LD. We experimentally obtained high optical-optical conversion efficiency of close to 60% for the Nd:YVO₄ laser during CW operation. The output laser power is stable for the LD temperature of close to 40°C when using the VHG LD. The output laser power was calculated numerically to compare the experimental results. These experimental results will lead to the development of end-pump microchip lasers that do not require a temperature controller. The output laser power of the Nd:YVO₄ laser using the VHG LD was more than twice as high as that using the LD without VHG.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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