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High-Efficiency Hemispherical Short-Cavity Continuous-Wave Yb:YAG Laser by High-Intensity Pumping

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Abstract: Improving the efficiency of lasers without complex structures, expensive elements, and precise optimization will lead to cost reductions and increased practicality. Here, it is first shown theoretically that the dependence of the optical-to-optical conversion efficiency on the laser beam waist (minimum laser spot) radii for a Yb:YAG laser with a simple structure decreases extremely with increasing pump intensity and efficiency. Not only is the optimum range for highest efficiency wide, but even if the radii are doubled, the efficiency decreases by only a few percentage points or less at the maximum pump intensity of 450 kW/cm^2. Therefore, it is possible to achieve sufficiently high efficiencies without precise optimization by high-intensity pumping. In the experiment, at a pump wavelength of 940 nm, corresponding to pump-level pumping, the maximum efficiency was 75.2% for the incident pump power at the corresponding maximum intensity. On the other hand, at a pump wavelength of 968 nm, corresponding to direct pumping of the upper laser level, the maximum efficiency was 76.0% at about 60% of the maximum. Although the pump focus is slightly off from the optimum, these efficiencies are close to the theoretical maximum at the corresponding pump intensities. Since no complex gain medium is used, there is almost no efficiency reduction due to parasitic oscillations, despite the high pump intensities. These results demonstrate the high practicality of high-intensity pumping for high-efficiency lasers.

Keywords: high efficiency; high gain; high-intensity pumping; Yb lasers; quasi-four-level lasers; hemispherical cavity; pump-level pumping; direct pumping of the upper laser level

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1. Introduction

Highly efficient, compact, and lightweight solid-state lasers are particularly suited for mobile applications where size and weight are constraints, and they can be used efficiently with batteries that have a limited capacity per unit weight. If laser efficiency can be improved with a simple configuration without expensive elements and precise adjustments, it will lead to cost reductions. Cost reduction is an important requirement for expanding application areas. However, there is a problem of reduced efficiency due to the loss of low-cost optical components such as saturable absorbers for short pulses. Yb-based laser gain media [1,2], referred to as quasi-three-level lasers [3] or quasi-four-level lasers [4,5], are suitable for high-efficiency lasers due to their high quantum efficiency. However, they have the disadvantage of losses due to thermal excitation to the lower laser level [1–4], which will be referred to as quasi-four-level laser losses in this paper. Currently, cryogenically cooled lasers [2,6,7], which require a cooling system capable of cooling to cryogenic temperatures; thin-disk lasers [8–10], which are useful for a high average laser power but require multi-path pumping optics; and fiber lasers [11–13], which are also useful for a high average laser power but are limited in beam area expansion near the fundamental mode oscillation due to their use of waveguides, are used to improve the efficiency of Yb-based lasers.

In contrast, high gain by high-intensity pumping [14–16] is a simple, low-cost method that does not require large or complex cooling and optical systems for cryogenic cooling or multi-path pumping and is suitable for miniaturization. Compared to fiber lasers, the mode area can be easily expanded, making it suitable for high-energy pulse output. The efficiency reduction due to quasi-four-level laser loss is also overcome by high-intensity pumping, and the efficiencies (the optical-to-optical conversion efficiency of continuous wave (CW) and nanosecond pulsed lasers for the incident pump power is up to 81% and 62%, respectively [14–17]) are comparable to or better than those of cryogenically cooled lasers (the optical-to-optical conversion efficiency of CW lasers is up to 76% [7,17]) or other high-efficiency techniques, such as the multi-path pumping of thin disks (the optical-to-optical conversion efficiency of CW and nanosecond pulsed lasers is up to 72% and 45%, respectively [10,11,17]) or fiber lasers (the optical-to-optical conversion efficiency of CW lasers is up to 81% [13,17]). In addition, the high gain by high-intensity pumping is suitable for suppressing the efficiency reduction due to losses, including quasi-four-level laser loss.

In this study, the efficiency of a hemispherical short-cavity Yb:YAG laser was improved by high-intensity pumping. First, by analyzing a theoretical model that incorporates the spatial distribution of the laser and pump modes into the rate equations, it was found that the dependence of the optical-to-optical conversion efficiency on the laser beam waist (minimum laser spot) radii decreases extremely with increasing pump intensity. This decrease in dependence becomes more pronounced as the optical-to-optical conversion efficiency increases. Not only is the optimal range of the laser beam waist radii for maximum efficiency wide, but even if the laser beam waist radii deviate twice from the optimal range, the efficiency decreases by only a few percentage points or less at the corresponding maximum pump intensity of 450 kW/cm^2. In the experiment, the highest optical-to-optical conversion efficiency of 75.2% was achieved for the corresponding maximum pump intensity at a wavelength of 940 nm, which is often used for the pump-level pumping of the Yb:YAG. On the other hand, at a pump wavelength of 968 nm, which is often used for direct pumping of the upper laser level [18,19] of the Yb:YAG, the highest optical-to-optical conversion efficiency of 76.0% was achieved at a pump intensity of 260 kW/cm^2, about 60% of the corresponding maximum pump intensity. For the sake of simplicity, direct pumping of the upper laser level will be referred to as direct pumping in the following. The reason why the pump intensity that gives the highest efficiency for direct pumping is only about 60% of the maximum is considered to be because the pump absorption saturation is not resolved when the laser oscillates at a higher pump intensity. These experimental efficiencies are close to the theoretical maximum optical-to-optical conversion efficiency, even though the pump-focusing conditions slightly deviate from the optimum for high-intensity pumping. These facts also show that in the case of Yb:YAG lasers, for example, despite a high pump intensity of more than 100 kW/cm^2, the reduction in efficiency due to parasitic oscillations caused by the high gain, the temperature increase, and thermo-optic distortion of the gain medium caused by the high pump intensity can be ignored.

To the best of our knowledge, some of the short-cavity or microchip lasers using quasi-four-level lasers as gain media have high optical-to-optical conversion or slope efficiencies for the absorbed pump power (e.g., a slope efficiency of 91% [17,20]). However, due to a relatively low pump absorption efficiency or a relatively high oscillation threshold, the true efficiency of the optically pumped laser, the optical-to-optical conversion efficiency for the incident pump power, was not very high (up to 49% [17,20,21]). In contrast, the laser in this study has not only a high optical-to-optical conversion efficiency for the absorbed pump power but also a high optical-to-optical conversion efficiency for the incident pump power. The optical-to-optical conversion efficiencies for the incident pump power obtained in the experiment are about 1.6 times higher than the efficiencies of conventional short-cavity and microchip lasers using quasi-four-level lasers as the gain medium. There are various efficiencies for lasers, but in this paper, the true efficiency of the optically pumped laser, i.e., the optical-to-optical conversion efficiency for the incident pump power, is expressed as the optical-to-optical conversion efficiency or simply the efficiency.

2. Materials and Methods

2.1. Experiment with the Hemispherical Short-Cavity Yb:YAG Laser

A schematic diagram of the experiment is shown in Figure 1. The laser cavity was a hemispherical cavity, which is advantageous in terms of miniaturization and simplification. The gain medium geometry, coating, and cooling configuration were the same as those used in previous studies [17]. A Yb:YAG crystal (Scientific Materials Corp., 900 Technology Blvd, Bozeman, MT 59718, USA) with a slightly wedge-shaped surface was used as the microchip gain medium. The outer surface (the left side of the Yb:YAG), where the pump beam entered, served as the end mirror for the laser cavity and was coated with an anti-reflection coating for the pump wavelengths and a high-reflection coating for the laser wavelengths. The inner surface (right) was coated with an anti-reflection coating for the pump and laser wavelengths. The Yb:YAG was adhered to a slightly wedged sapphire plate of the same vertical and horizontal width as the Yb:YAG, with anti-reflection coatings on both surfaces for the pump and laser wavelengths. The adhered surfaces were the outer surface (right) of the Yb:YAG and one of the anti-reflective coated surfaces of the sapphire. The thermal conductivity of the materials used in the dielectric multilayer coating and the adhesive are several orders of magnitude different from the thermal conductivity of the Yb:YAG and the sapphire, so the surface thermal resistance of this interface tends to be large due to the impedance mismatch of heat transport. According to the heat transport theory, the maximum temperature increase in the gain medium is low at about 10 °C even without this scheme, so this cooling scheme, with the limited cooling efficiency (low thermal conductance) of the gain medium, was used to cool the gain medium. The ensemble (manufactured by OPTOQUEST CO., LTD., 1335 Haraichi, Ageo, Saitama 362-0021, Japan) was mounted on a copper heat sink for cooling. The heat sink was kept at room temperature (approximately 20 °C) by a thermoelectric cooler.

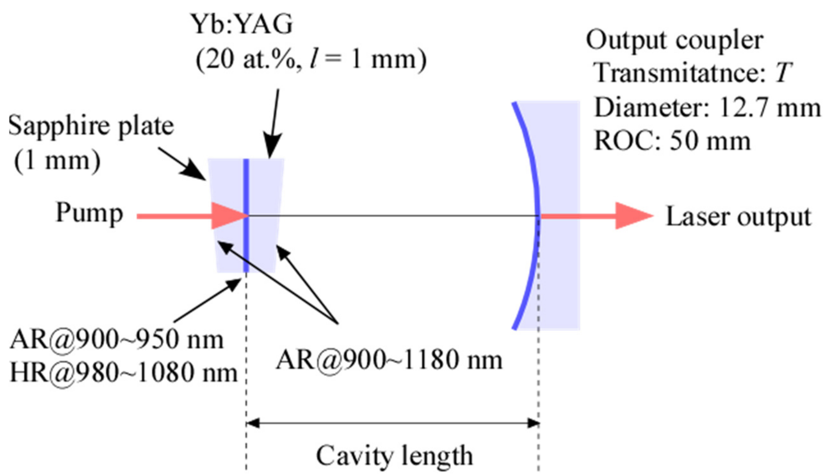


Figure 1. Schematic diagram of the hemispherical short-cavity Yb:YAG laser. HR is high-reflection coating, AR is anti-reflection coating. ROC is the radius of curvature of the output coupler.

The transmittance T of the output coupler, with a radius of curvature of 50 mm, was set to 2%, 4.5%, and 5%, respectively, for the experiments. The diameter of the output coupler was 12.7 mm. The pump source was a CW Ti/sapphire laser (3900S, Spectra-Physics, 1565 Barber Lane Milpitas, CA 95035, USA). The pump wavelengths used in the experiment were 940 nm, corresponding to pump-level pumping of the Yb:YAG, and 968 nm, corresponding to direct pumping of the Yb:YAG. A polarizer and a half-wave plate were used to adjust the incident pump power without varying the pump spot positions and sizes. The maximum incident pump power in the experiment was 750 mW. The focal length of the focusing lens was 20 mm. The unsaturated single-pass pump absorption efficiencies were measured to be 82% for the 940 nm wavelength and 80% for the 968 nm wavelength. After passing through the gain medium, the pump beam is reflected by the output coupler and re-enters the gain medium. The corresponding pump absorption efficiency is the condition under which the storage efficiency of the gain medium [22] is close to maximum at the maximum pump intensity in the experiment. At this pump absorption efficiency, the length of the gain medium is approximately 1 mm when the concentration of Yb ions is 20 at.%. Therefore, the concentration of Yb ions was set to 20 at.%, and the length of the gain medium was set to 1 mm. By optimizing the pump absorption efficiency, not only the slope efficiency and the optical-to-optical conversion efficiency for the absorbed pump power, which are only apparent laser efficiencies, but also the optical-to-optical conversion efficiency for the incident pump power, which is the actual laser efficiency, can be improved [14]. The higher the pump intensity, the higher the optimum pump absorption efficiency, and thus the optical-to-optical conversion efficiency for the incident pump power can be further increased [14,17,22].

At a pump wavelength of 968 nm, the vertical and horizontal beam quality M^2 factors were measured to be 1.2 and 1.1, respectively, and were nearly identical at a pump wavelength of 940 nm. The minimum spot radii in the experiment were 10.9 µm and 9.7 µm in the vertical and horizontal directions, respectively. The difference in focusing position between the horizontal and vertical directions was relatively large at about 0.5 mm, but it was shorter than the length of the gain medium, the confocal length, and the corresponding thermal focal length, so it was used as it was in the experiment. These values were used for the theoretical analysis, except for the difference in the focusing position. In the theoretical analysis, the focusing position is assumed to be the same in the horizontal and vertical directions. The corresponding maximum pump intensity is 450 kW/cm^2 when the intensity distribution of the pump beam is assumed to be a Gaussian beam profile with the same radii as the measured minimum spot radii. Also, the optimal minimum spot radii for minimizing the pump mode volume at a pump wavelength of 968 nm, and assuming that the Gaussian beam with beam quality M^2 factors in the experiment was focused on the end mirror side of the cavity (the left side of the gain medium in Figure 1), were 11 µm and 10 µm in the vertical and horizontal directions, respectively. In summary, although the focal spot radii of the experiment were almost close to the minimum condition of the pump mode volume, the focusing position was relatively offset, so the resulting pump focusing condition slightly deviated from the minimum condition of the pump mode volume. Simply put, the maximum pump intensity in the experiment was slightly lower than the corresponding pump intensity of 450 kW/cm^2. However, for the sake of simplicity in the explanation in this paper, the maximum pump intensity in the experiment is expressed as the corresponding maximum pump intensity or simply the maximum pump intensity of 450 kW/cm^2.

2.2. Quasi-Four-Level Laser Theory Including the Spatial Distribution of Pump and Laser Modes

The theoretical analysis uses quasi-four-level laser rate equations with CW pumping, which include the spatial distribution of the pump and laser modes in the gain medium [17,23–26]. These are well-known theories, but the various definitions differ for each theory. The theory in this paper has been optimized for the case of this study, i.e., to analyze the dependence of the optical-to-optical conversion efficiency on the beam waist radii and the input–output characteristics in the case where the beam radii of the lasers and pumps are distributed inside the gain medium. In contrast, conventional theories assume that the beam radii in the gain medium are fixed. Therefore, this is discussed in detail below. The optical-to-optical conversion efficiency $\eta_{\rm oo}$ for the incident pump power on the gain medium $P_{\rm P}$ is defined by the ratio between the laser output power $P_{\rm o}$ and the incident pump power $P_{\rm P}$, and is given by the normalized intracavity laser power S and the normalized incident pump power F as

$$\eta_{\rm oo} \equiv \frac{P_{\rm o}}{P_{\rm p}} = \eta_{\rm c}\eta_{\rm p}\eta_{\rm q}\eta_{\rm a}\frac{S}{F}\,, \tag{1}$$

where the coupling efficiency between the laser output power $P_{\rm o}$ and the intracavity laser powers is $\eta_{\rm c} \equiv T/L$, which is an approximation when the output coupler transmittance T is small (at most 5%), as in this paper. The total loss of the laser cavity, excluding the quasi-four-level laser loss, is L. The pump quantum efficiency is $\eta_{\rm p}$, and the pump absorption efficiency is $\eta_{\rm a}$. The atomic quantum efficiency is $\eta_{\rm q} \equiv (h\nu_{\rm L})/(h\nu_{\rm p})$, where the laser photon energy is $h\nu_{\rm L}$ and the pump photon energy is $h\nu_{\rm p}$. The normalized incident pump power F is dimensionless with respect to the incident pump power $P_{\rm p}$, defined by

$$F \equiv \frac{2f\sigma_{\rm em}\,\tau\, l\, \eta_{\rm p}\, \eta_{\rm a}\, P_{\rm p}}{h\nu_{\rm p}\, L\, V_{\rm L}}\,, \tag{2}$$

and the normalized intracavity laser power S, which is dimensionless with respect to the intracavity laser power $P_{\rm o}/T$, defined by

$$S \equiv \frac{2f\sigma_{\rm em}\,\tau\, l\, P_{\rm o}}{h\nu_{\rm L} V_{\rm L}\, T}\,, \tag{3}$$

where the gain medium length is l, the stimulated emission cross section is $\sigma_{\rm em}$, the lifetime is τ, and the laser mode volume in the gain medium is $V_{\rm L}$ [17]. The sum of the localized Boltzmann distribution of the lower laser level f_1 and the upper laser level f_2 is defined as $f \equiv f_1 + f_2$.

From the condition that the amplified and lost intracavity laser powers are equal in steady-state CW laser oscillation, the relationship between the normalized incident pump power F and the normalized intracavity laser power S is given by

$$F = \frac{1 + \frac{2f_1 n_{\rm L}\sigma_{\rm em}\, l}{L}\int \frac{\phi_{\rm o}}{1+S\,V_{\rm L}\,\phi_{\rm o}}dV}{V_{\rm L}\int \frac{r_{\rm p}\,\phi_{\rm o}}{1+S\,V_{\rm L}\,\phi_{\rm o}}dV}\,, \tag{4}$$

where the laser ion concentration is $n_{\rm L}$. Equation (4) is obtained because when the intracavity loss is small (at most about 5%, the maximum transmittance of the output coupler), the intracavity laser power is assumed to be nearly uniformly distributed, and the lost intracavity laser power can be approximated as the product of the intracavity power and the total loss in the cavity L [25]. The pump distribution function $r_{\rm p}$ and the laser distribution function $\phi_{\rm o}$ are normalized by the volume integral in the gain medium as $\int r_{\rm p} dV = \int \phi_{\rm o} dV = 1$.

These distribution functions are defined by the spot positions, radii, and beam qualities of the pump and laser beams.

Since the normalized incident pump power F and the normalized intracavity laser power S, which are the normalized values of the incident pump power P_{p} and the intracavity laser power, should theoretically be dimensionless quantities, they are both normalized here by the laser mode volume V_{L} (in previous studies, they were not dimensionless quantities [25,26]). Of course, the optical-to-optical conversion efficiency η_{oo} and the output power P_{o} do not change when the normalized incident pump power F and the normalized intracavity laser power S are both normalized by the pump mode volume V_{P}. Therefore, when calculating the optical-to-optical conversion efficiency as a function of the laser beam waist radii while keeping the pump beam waist (minimum pump spot) radii fixed, this is easier to understand when they are normalized by the pump mode volume V_{p}. Equation (4) is an expression of the normalized incident pump power F as a function of the normalized intracavity laser power S, i.e., $F = F(S)$, and above the oscillation threshold

$$F_{\mathrm{th}} = \left(1 + \frac{2f_1 n_{\mathrm{L}} \sigma_{\mathrm{em}}\, l}{L}\right) \frac{V_{\mathrm{eff}}}{V_{\mathrm{L}}}\,, \tag{5}$$

F and S have a one-to-one relationship, where the effective mode volume between the laser and pump modes in the gain medium is defined by using the pump distribution function r_{p} and the laser distribution function ϕ_{o} as

$$V_{\mathrm{eff}} \equiv \frac{1}{\int r_{\mathrm{p}}\, \phi_{\mathrm{o}} dV}\ . \tag{6}$$

Therefore, by fixing the pump and laser spot radii and positions, determining the pump distribution function r_{p}, and the laser distribution function ϕ_{o}, deriving the laser output power P_{o} as a function of the incident pump power P_{p} is simply the reverse of obtaining the incident pump power P_{p} as a function of the laser output power P_{o}, so Equation (4) can be used as is. On the other hand, if we want to obtain the optical-to-optical conversion efficiency as a function of the laser or pump spot radii while keeping the incident pump power P_{p} fixed, it is necessary to obtain the normalized intracavity laser power S as a function of the normalized incident pump power F, i.e., $S = S(F)$ from Equation (4). The reason for this is that the relationship between the normalized intracavity laser power S and the normalized incident pump power F varies as the pump distribution function r_{p} or the laser distribution function ϕ_{o} varies, caused by these radii variations.

The conditions and parameters used in the theoretical analysis are as follows. The physical parameters of the gain medium in the analysis, such as the emission cross-section σ_{em} and the lifetime τ, were taken from the literature [27–29]. The temperature of the gain medium was set to a room temperature of 20 °C, since the maximum temperature increase at maximum pump power in a theoretical analysis is only about 10 °C [17]. The gain medium length l and the laser ion concentration n_{L} were identical to those in the experiment (measured by the manufacturer). The intrinsic residual loss was 0.2% and was obtained from the analysis of Findlay and Clay [30] just near the boundary on the stable region side between the stable and unstable regions. The reason for using this analysis is that just near the boundary, the effective mode volume V_{eff} is kept almost to a minimum regardless of the change in cavity loss and the corresponding oscillation threshold. Therefore, the effective mode volume V_{eff} is considered to be almost constant regardless of the magnitude of the thermo-optic distortion, and the assumption of the analysis is maintained [17]. The pump absorption efficiency η_{a} and the pump distribution function r_{p} were assumed to be that the pump beam is incident and absorbed by the gain medium, then reflected by the output coupler, which has the same reflectivity as the laser, and reabsorbed in the gain medium. The pump distribution function r_p was assumed to be a Gaussian beam profile with the same beam quality M^2 factors and spot radii in the vertical and horizontal directions as in the experiment. The pump spot positions were assumed to be at the end face of the gain medium (the left side of the gain medium in Figure 1). In other words, the difference between the horizontal and vertical pump spot positions in the experiment was ignored.

It is well known that the higher the pump intensity, the higher the pump absorption saturation. Under the conditions of this experiment, the pump intensity is high, and the higher the pump intensity, the higher the pump absorption saturation should be. However, according to most current laser theories, the pump absorption saturation disappears when the laser oscillates in both pump-level pumping and direct pumping. Therefore, the beam direction dependence of the pump distribution was assumed to decay exponentially with the unsaturated absorption coefficient obtained from the experiment. For the laser distribution function ϕ_o, a Gaussian beam profile and beam quality M^2 factors of 1.0 in the vertical and horizontal directions were assumed. Since the experiment used a hemispherical cavity with the gain medium as the end mirror, the laser was assumed to be focused on the end mirror side of the gain medium (the end faces of the gain medium and the cavity), as in the pump. Since gain saturation should occur when the laser oscillates, and since the cavity losses are small (at most about 5%, the maximum transmittance of the output couplers), the beam direction dependence of the laser distribution function was assumed to be constant.

3. Results

3.1. Theoretical Results for the Dependence of the Optical-to-Optical Conversion Efficiency on the Laser Beam Waist Radii

First, the dependence of the optical-to-optical conversion efficiency η_{oo} on the minimum vertical and horizontal laser spot radii for each output coupler transmittance was analyzed using the theory in Section 2.2. At the maximum pump power of 750 mW in the experiment and the corresponding maximum pump intensity of 450 kW/cm^2, the highest efficiency was slightly higher, within a few percentage points or less, at an oscillation wavelength of 1048 nm than at 1029 nm, when the laser beam waist radii were optimized. The reason why the efficiency is slightly higher at 1048 nm, where the atomic quantum efficiency and the stimulated emission cross-section are smaller but the quasi-four-level laser loss is also smaller, than at 1029 nm, where the atomic quantum efficiency and the stimulated emission cross-section are larger but the quasi-four-level laser loss is also larger, is that the intrinsic residual loss is relatively small at 0.2%. Of course, if the pump intensity is further increased, the efficiency for the 1029 nm oscillation will be higher than that for the 1048 nm oscillation, even though the quasi-four-level laser loss is higher. The efficiencies for output coupler transmittances of 4.5% and 5% were almost the same within an extremely small range of less than 0.1% point, which is the accuracy order of the efficiency, and were higher than that for 2%. As shown in the experiment in Section 3.2, the efficiency was highest at an output coupler transmittance of 5% and an oscillation wavelength of approximately 1050 nm, so the following theoretical analysis is shown under these conditions. At an output coupler transmittance of 5%, the highest optical-to-optical conversion efficiencies for the incident pump power are 75.8% for pump-level pumping and 77.2% for direct pumping, a small difference of 1.4% points. The corresponding optical-to-optical conversion efficiency for the absorbed pump power is 81.1% for direct pumping, which is relatively close to the quantum efficiency of 92.4%.

Figures 2 and 3 show examples of the dependence of the optical-to-optical conversion efficiency on the laser beam waist radii at the oscillation wavelength of 1048 nm and the output coupler transmittance of 5%. Figure 2 shows the dependencies for pump-level pumping and Figure 3 shows examples of the dependencies for direct pumping. Figures 2a,b and 3a,b show examples of the dependencies in a high pump intensity range, at the experimental maximum pump power of 750 mW and the corresponding pump intensity of 450 kW/cm^2. Figures 2c,d and 3c,d show examples of the dependencies in a conventional pump intensity range, at a pump power of 75 mW and corresponding pump intensity of 45 kW/cm^2, which are one tenth of the maximum values. Figures 2e,f and 3e,f show examples of the dependencies in a lower pump intensity range, at a pump power of 30 mW and corresponding pump intensity of 18 kW/cm^2, which are several times higher than the experimental oscillation thresholds. First, as a general trend, in the lower-efficiency ranges, as shown in Figures 2 and 3, the optical-to-optical conversion efficiency depends strongly on the laser beam waist radii. In particular, at low pump powers several times higher than the oscillation thresholds, as shown in Figures 2e,f and 3e,f, oscillation stops when the laser beam waist radii deviate, for example, by about twice the optimal values for maximum efficiency. Next, in the conventional pump intensity range, as shown in Figures 2c,d and 3c,d, the efficiency decreases by an order of 10% points when the pump beam waist radii deviate, for example, by about twice the optimal values. This tendency for the efficiency to be strongly dependent on the radii is well known as a convention. The reason can be explained using the theory in Section 2.2, as follows: In the low-efficiency region, the intracavity laser intensity is low, and the corresponding normalized intracavity laser power S in Equation (4) is also low, and the efficiency depends strongly on the geometric overlap between the pump and laser mode distribution functions r_{p} and ϕ_{o}. In particular, the laser oscillation threshold increases proportionally to the effective mode volume V_{eff}, as shown in Equation (5). The smaller the geometric overlap between the pump and laser mode distribution functions r_{p} and ϕ_{o}, the larger the effective mode volume V_{eff} and the higher the oscillation threshold, so the efficiency also decreases.

On the other hand, the higher the efficiency by increasing the pump intensity, the less the optical-to-optical conversion efficiency depends on the laser beam waist radii. The analysis results show that the dependence of the optical-to-optical conversion efficiency on the laser beam waist radii decreases near the maximum efficiency as the cavity loss decreases and the pump intensity increases. For example, at the maximum pump intensity for pump-level pumping shown in Figure 2a,b, the laser beam waist radii that give the highest efficiency within an error range of about 0.1% points or less are in the range of 10 μm to 16 μm in the vertical axis and 9 μm to 11 μm in the horizontal axis. Also, at the maximum pump intensity for direct pumping shown in Figure 3a,b, the laser beam waist radii for the highest efficiency within the error range are in the range of 10 μm to 16 μm in the vertical axis and 8 μm to 10 μm in the horizontal axis. The ranges of optimal spot radii for pump-level pumping and direct pumping are several tens of percent of the central values and almost overlap. Furthermore, even if the range of spot radii varies by a factor of two from the highest efficiency condition, the reduction in efficiency is limited to a few percentage points or less. In particular, the fact that the efficiency does not decrease significantly with increasing laser beam waist radii (namely, a decrease of a few percentage points or less at twice the pump beam waist radii) is useful for reducing damage to gain media and coatings and is advantageous for increasing the energy and peak power of pulsed lasers, considering that laser-induced damage occurs mostly at the focused surface.

The reason why the optical-to-optical conversion efficiency becomes less dependent on the laser beam waist radii as the efficiency increases by increasing the pump intensity is as follows. First, to increase the efficiency, it is important to balance the reduction in the oscillation threshold and the improvement in the slope efficiency $dP_{\mathrm{o}}/dP_{\mathrm{p}}$, and the ratio of the normalized in-cavity laser power S to the normalized incident pump power F must be increased, as shown in Equation (1) in Section 2.2. The effective mode volume V_{eff}, which represents the geometric overlap between the pump and laser modes, as defined in Equation (6) in Section 2.2, is only proportional to the oscillation threshold, as mentioned above. To reduce the oscillation threshold, it is necessary to optimize the laser and pump mode distributions to reduce the effective mode volume V_{eff}. In other words, the only direct consequence of a small geometric overlap is a higher oscillation threshold. Of course, no matter how high the threshold is, the efficiency reduction due to a high threshold can be reduced by increasing the pump intensity. More simply, the higher the pump intensity is above the laser oscillation threshold condition (the corresponding equation is Equation (5)), the less the laser oscillation threshold will affect the efficiency. In fact, the effect of this geometric distribution optimization becomes less significant as the optical-to-optical conversion efficiency is increased by high-intensity pumping. This is because the intracavity laser intensity increases, and the corresponding normalized intracavity laser power S also increases, as the optical-to-optical conversion efficiency is increased by high-intensity pumping. Far above the oscillation threshold, the mode-matching efficiency between the pump and laser beams, which is proportional to the slope efficiency $dP_{\mathrm{o}}/dP_{\mathrm{p}}$, depends more on the intracavity laser intensity than on the geometric overlap. The higher the intracavity laser intensity, the higher the mode-matching efficiency and the less the dependence on the geometric overlap. Under conditions of high pump intensity, the intracavity laser intensity is also high at high efficiency.

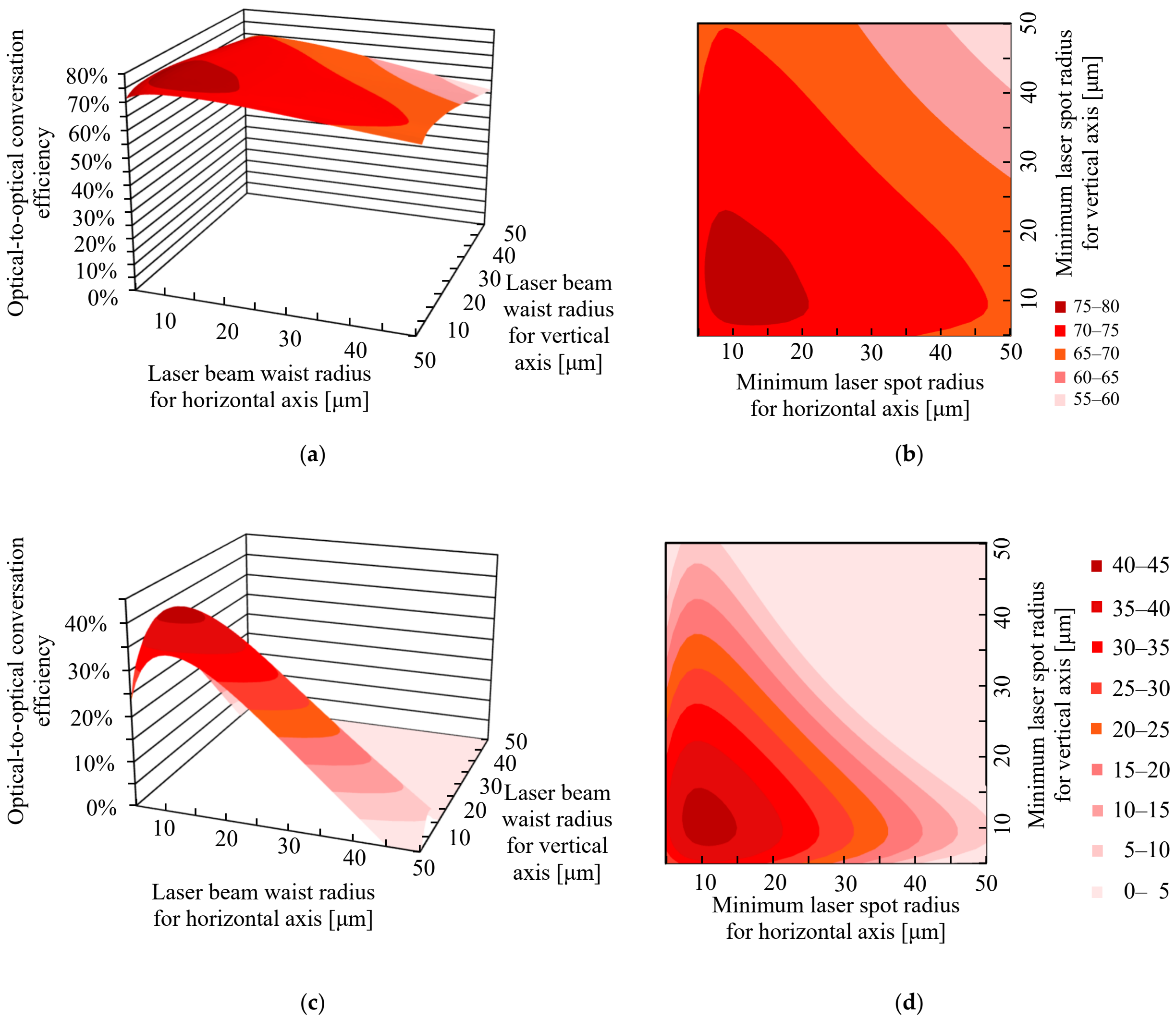
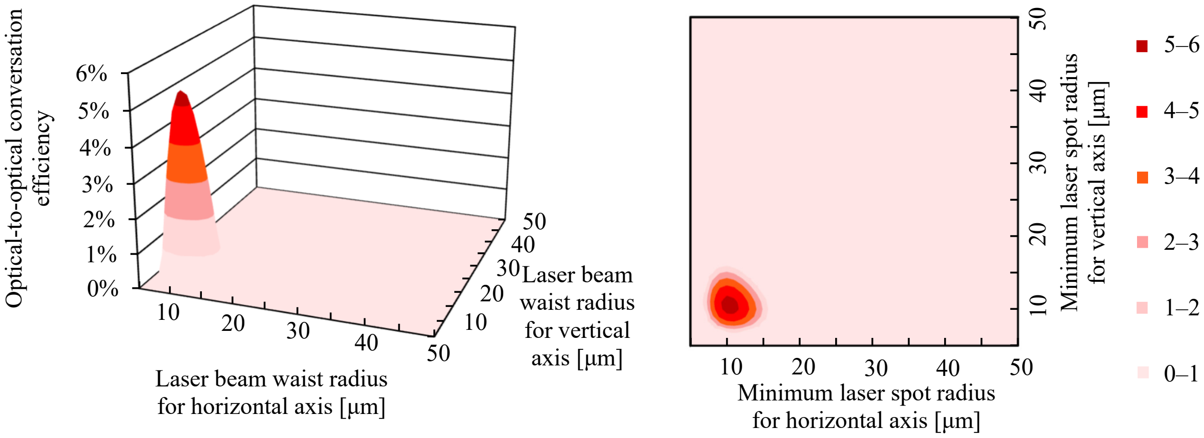


Figure 2. *Cont.*



(**e**) (**f**)

Figure 2. The optical-to-optical conversion efficiency as a function of the laser beam waist radii for the vertical and horizontal axes for pump-level pumping. The oscillation wavelength and output coupler transmittance are 1048 nm and 5%, respectively. The figures in the left column are 3D plots, and the figures in the right column are contour maps of the same data with the same legends. The correspondence between the legends and the efficiencies is shown in the figures in the right column, where the higher the efficiency, the darker the red, and the lower the efficiency, the lighter the red. The pump powers for (**a**,**b**) are 750 mW, which is the maximum pump power of the experiment; for (**c**,**d**) are 75 mW, which is one-tenth of the maximum pump power; and for (**e**,**f**) are 30 mW, which is several times higher than the oscillation thresholds of the experiment.

In other words, the higher the pump intensity, the smaller the effect of the oscillation threshold, which also means the smaller the effect of the gain product $\sigma_{em}\ \tau$ and the quasi-four-level laser loss $2f_1 n_L \sigma_{em}\ l$ on the optical-to-optical conversion efficiency [17]. Since the gain product is the proportional coefficient of the gain for CW pumping, its accuracy and magnitude have been considered extremely important, and many studies have been conducted on this topic. Since the quasi-four-level laser loss has also been considered a serious drawback of quasi-four-level lasers in the past, great efforts have been made to improve the cooling efficiency (thermal conductance) of the gain medium of quasi-four-level lasers. For example, much effort has been devoted to improving the surface thermal conductance between the gain medium and the heat sink in thin disks and microchips due to the small cooling area. There have also been many studies on the cryogenic cooling of the gain medium. In contrast, the pump power in this paper is small, at about 1 w; however these facts show that high efficiency by high-intensity pumping can be a simple technology to reduce these efforts. To improve the mode-matching efficiency, many efforts have also been made on gain media with complex structures that combine undoped and gain media (for example, [5]). The result that the efficiency does not decrease significantly even when the laser beam waist radii are several times larger than the pump beam waist radii also implies that the need for complex structures of the gain medium is also reduced by high-intensity pumping.

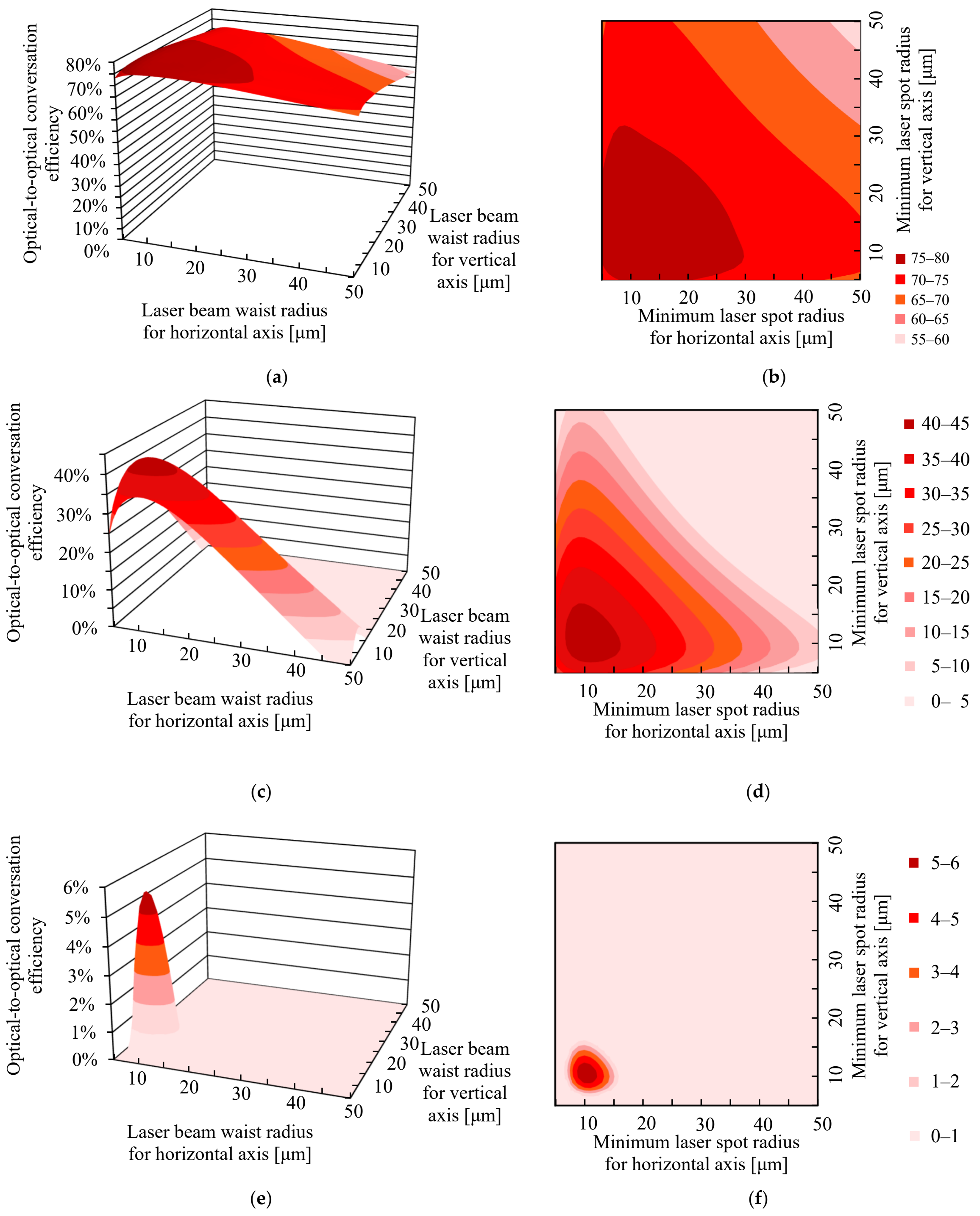


Figure 3. The optical-to-optical conversion efficiency as a function of the laser beam waist radii for the vertical and horizontal axes for direct pumping. As in Figure 2, the oscillation wavelength and output coupler transmittance are 1048 nm and 5%, respectively. The correspondence between the graphs in the left and right columns and the legends are the same as in Figure 2. The pump powers for (**a**,**b**) are 750 mW, which is the maximum pump power; for (**c**,**d**) are 75 mW, which is one-tenth of the maximum pump power; and for (**e**,**f**) are 30 mW, which is several times higher than the oscillation thresholds of the experiment, respectively, the same as in Figure 2.

3.2. Experimental Results for Input–Output Characteristics

In the following, the dependence of the output power on the incident pump power is simply referred to as the input–output characteristics. In the experiment, the laser cavity and its stability conditions were determined and adjusted by the following method, and the laser mode was optimized to improve the laser efficiency. First, the cavity stability conditions for the high efficiency of a short-cavity laser at high pump intensity are explained. It is known that when the thermal lens focal length is finite, the stable region of a hemispherical cavity is divided into two parts: the first stable region (shorter cavity length) and the second stable region (longer cavity length) [17,31,32]. When the pump intensity is high (i.e., the corresponding maximum pump intensity is 450 kW/cm^2) and the corresponding thermal lens focal length in the gain medium (a few mm in the thin-lens approximation at the corresponding maximum pump intensity) is shorter than half the radius of curvature of the output coupler (25 mm), as in this experiment, the first stable region starts at a cavity length of 0 mm, and the second stable region starts at the radius of curvature [17]. Therefore, to shorten the cavity length using the second stable region, it is sufficient to use an output coupler with a short radius of curvature. To further shorten the cavity length, it is better to use the first stable region, where the corresponding cavity length is much shorter than that of the second stable region, because the corresponding stable region starts at a cavity length of 0 mm. However, according to the analysis of laser beam propagation by the ABCD matrix, which includes the thermo-optic distortion of the gain medium as a quadratic distribution medium, the optimum cavity length in the first stable region for the highest efficiency is shorter than the length of the gain medium in the experiment (1 mm). Therefore, the second stable region was used in the experiment to achieve the highest efficiencies.

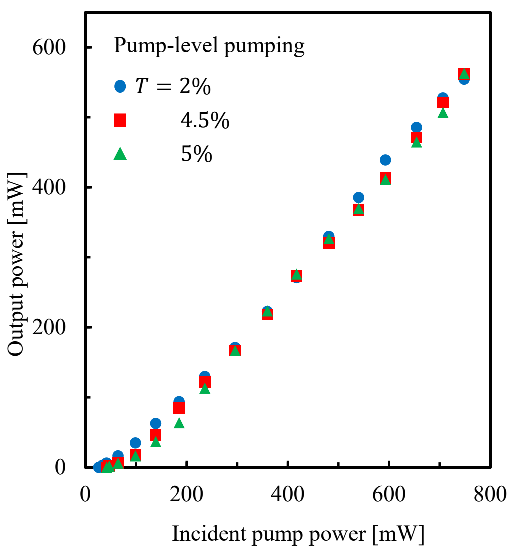
Of course, it is easy to shorten the length of the gain medium, while maintaining the optimum absorption efficiency for the highest optical-to-optical conversion efficiency for the incident pump power, by using a higher concentration of Yb ions in the gain medium than that used in the experiment. For example, when the Yb ion concentration is 100 at.%, that is, when YbAG is used as the gain medium, the optimum length of the gain medium is about 0.2 mm. This length is sufficient to make the cavity length long enough to achieve the highest efficiency. Gain medium with a high ion concentration is often considered problematic because of a decrease in the gain product due to concentration quenching (lifetime reduction) and an increase in the quasi-four-level laser loss due to the temperature increase caused by pumping. As mentioned in Section 3.1, all these problems of laser efficiency reduction can be solved by high-intensity pumping. Namely, the gain decrease due to the small gain product caused by the high ion concentration can be overcome by increasing the pump intensity. When the maximum pump power is relatively low, about 1 W, as in this experiment, the maximum temperature increase when YbAG is used as the microchip gain medium in the experiment is also kept relatively low, about 50 °C. (If the shape of the gain medium is the same except for the length, the thermal conductance is proportional to the length [17]. Therefore, if the temperature increase is about 10 °C when the length of the gain medium is 1 mm, it will be about 5 times that, or 50 °C, when it is 0.2 mm.) With a temperature increase of this magnitude, the gain medium will not be damaged, and the efficiency reduction caused by the quasi-four-level laser loss can be sufficiently overcome by high-intensity pumping, as also mentioned in Section 3.1.

However, the only way to avoid damage to the gain medium due to temperature increase is to reduce the temperature increase of the gain medium. To achieve this, it is necessary to increase the gain medium cooling area to increase the thermal conductance between the gain medium and the heat sink, reduce the distance between the pumping and cooling regions, and narrow the pumping regions or use a gain material with high thermal conductivity to reduce the temperature increase in these regions, thereby increasing the cooling efficiency (thermal conductance) of the gain medium [17]. For this reason, it was previously thought that the high thermal conductivity of the gain medium was also important. Since the thermal conductivity is the proportional coefficient of the cooling heat flow density and the temperature gradient, it is true that the higher the thermal conductivity, the smaller the temperature gradient in the gain medium for a constant cooling heat flow density [33,34]. On the other hand, the narrower the distance between the pumping and cooling regions, the smaller the temperature increase in these regions. Therefore, what is important for reducing the temperature increase in the gain medium with these narrowed regions is not the high thermal conductivity of the gain medium but the high surface thermal conductance between the cooling surface of the gain medium and the heat sink. To increase the cooling efficiency without using a gain medium with high thermal conductivity, structures such as thin rods [20] or thin slabs [35,36], which have a thin thickness for the cooling axis and a large cooling area for the gain medium, are more suitable than the microchip or thin-disk structure of the gain medium used in this study. For these reasons, high-intensity pumping has the potential to be a game changer in high-efficiency laser technology.

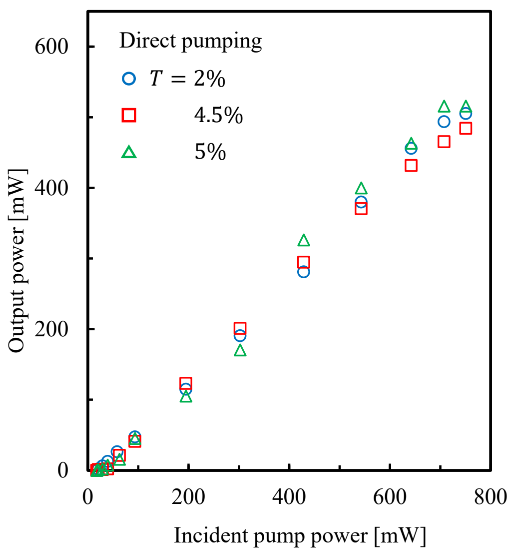
Next, the method of adjusting the laser in the experiment is explained. For each of the pump-level pumping and direct pumping activities, first at the maximum pump power, the cavity and its length and the pump spot position were adjusted to obtain the maximum output power with a near-basic Gaussian beam. Then, the pump power was gradually decreased from the maximum pump power, and the cavity was adjusted to obtain the maximum output power under the first fixed cavity length at the maximum pump power. Since the thermo-optic distortion that affects the cavity stability condition depends on the pump intensity, the pump power that gives the most efficient cavity stability conditions in this experimental method is the maximum pump power. By adjusting the laser in this way, it is possible to optimize the cavity stability conditions for high efficiency at any pump power intensity, so that precise measurement of thermo-optic distortion and precise cavity design are no longer necessary, regardless of whether the pump intensity is high or low. On the other hand, as the pump power is reduced from the maximum pump power, the stability conditions may deviate from those under which the optimum laser mode for maximum efficiency is obtained at that pump power because the thermo-optic distortion varies.

Experimental results and a brief discussion follow. Figure 4 shows the input–output characteristics of the hemispherical cavity Yb:YAG laser. Figure 4a summarizes the result of pump-level pumping, and Figure 4b summarizes the result of direct pumping. First, as shown in Figure 4a, the input–output characteristics for pump-level pumping were nearly linear well above the oscillation threshold, and saturation was almost not observed. The maximum output power and optical-to-optical conversion efficiency were achieved for all output coupler transmittances at the maximum pump power of 750 mW. On the other hand, as shown in Figure 4b, the input–output characteristics for direct pumping were nearly linear well above the oscillation threshold, but they tended to saturate as the pump power approached the maximum. Figure 4c–e summarize the results for each output coupler transmittance, to compare the results of pump-level pumping and direct pumping. As shown in these figures, for all output coupler transmittances, the output power tended to be slightly higher for direct pumping when the pump power was small. On the other hand, the output power of pump-level pumping tended to be slightly higher when the pump power was higher. For pump-level pumping, the maximum optical-to-optical conversion efficiency for the incident pump power was obtained at the maximum pump power. The maximum efficiencies were 74.1%, 75.0%, and 75.2% for output coupler transmittances of 2%, 4.5%, and 5%, respectively. The optical-to-optical conversion efficiency for absorbed pump power at a 5% output coupler transmittance is 78.3%. In contrast, for direct pumping, the incident pump power at which the maximum optical-to-optical conversion efficiency was obtained was not the maximum pump power. The incident pump power and conversion efficiency at which the maximum conversion efficiency was obtained were 642 mW and 71.0%, 429 mW and 68.7%, and 429 mW and 76.0% for output coupler transmittances of 2%, 4.5%, and 5%, respectively. The maximum optical-to-optical conversion efficiency for the absorbed pump power at a 5% output coupler transmittance is 79.8%.

For pump-level pumping, the laser wavelength was shifted at output coupler transmittances of 4.5% and 5%, but not at 2% transmittance. At output coupler transmittances of 4.5% and 5%, the laser wavelength shifted from approximately 1030 nm to approximately 1050 nm at incident pump powers above 190 mW and 250 mW, respectively. At an output coupler transmittance of 2%, the laser operated only at approximately 1050 nm. On the other hand, with direct pumping, the laser oscillation wavelength shifted only at an output coupler transmittance of 5%, and the laser oscillation wavelength shifted from approximately 1030 nm to approximately 1050 nm when the incident pump power was 430 mW or higher. At output coupler transmittances of 2% and 4.5%, the laser operated only at approximately 1050 nm. For pump-level pumping, the atomic quantum efficiencies are 91.4% at 1029 nm and 89.8% at 1048 nm. On the other hand, for direct pumping, the atomic quantum efficiencies are 94.1% at 1029 nm and 92.4% at 1048 nm. These differences in atomic quantum efficiency due to the oscillation wavelength shift should appear in the experiment mainly as differences in efficiency and input–output characteristics. However, as shown in Figure 4, little effect on the input–output characteristics and efficiency was observed in the experiment. The maximum optical-to-optical conversion efficiencies are almost the same as those for pump-level pumping and direct pumping. The reason may be that the difference in quantum efficiency caused by wavelength shift and pumping scheme is small. In general, for direct pumping, wavelength stabilization and the narrowing of the pump source are important to improve the pump absorption efficiency due to its narrow absorption spectrum. On the other hand, for pump-level pumping, wavelength stabilization and the narrowing of the pump source are not as important, because its absorption spectrum width is relatively wider than that of direct pumping. The fact that the maximum optical-to-optical conversion efficiency for pump-level pumping is sufficiently high to be almost the same as that for direct pumping means that the importance of wavelength stabilization and the narrowing of the pump sources is relatively low in terms of achieving high efficiency by high-intensity pumping, and this also leads to the cost reduction of pump sources such as laser diodes.

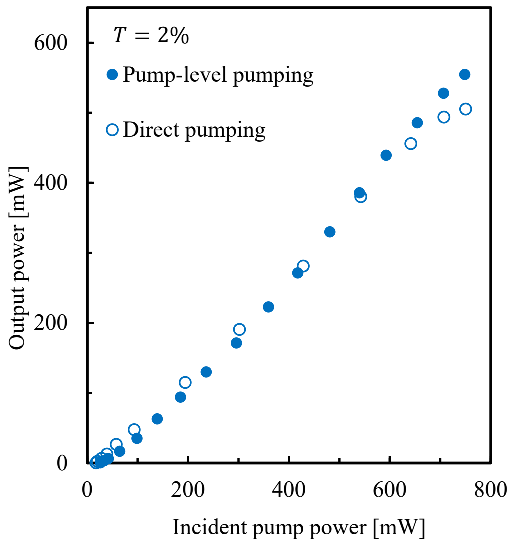


(a)

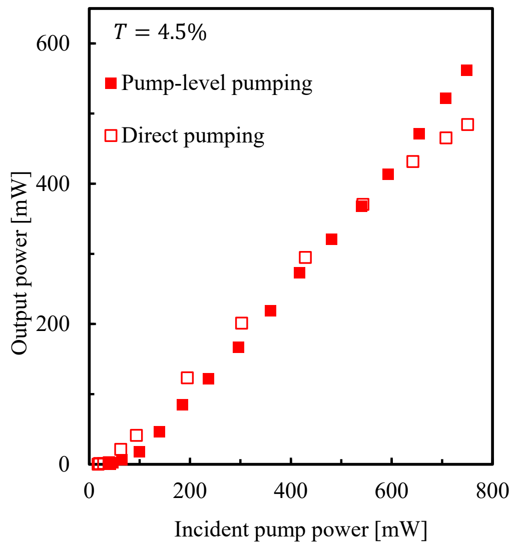


(b)

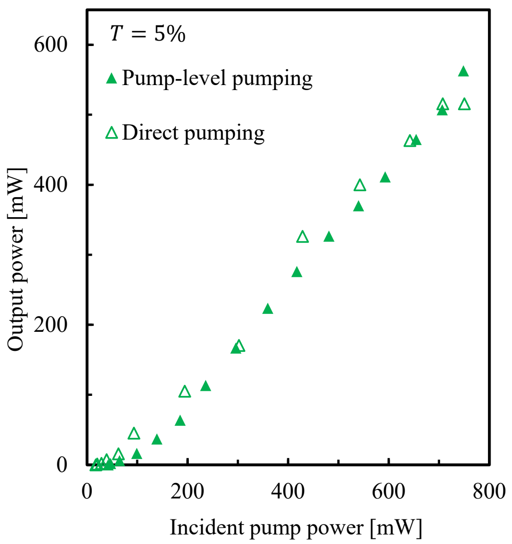
Figure 4. *Cont.*



(**c**)



(**d**)



(**e**)

Figure 4. Input–output characteristics of a hemispherical short-cavity Yb:YAG laser. Blue filled circles, red filled squares, and green filled triangles are results for output coupler transmittances of 2%, 4.5%, and 5%, respectively, for pump-level pumping. Blue empty circles, red empty squares, and green empty triangles are results for direct pumping for transmittances of 2%, 4.5%, and 5%, respectively. (**a**,**b**) show a comparison of the results for each transmittance for pump-level pumping and direct pumping, respectively. (**c**–**e**) show a comparison of the results for pump-level pumping and direct pumping for 2%, 4.5%, and 5% transmittances, respectively.

4. Discussion

As shown in Sections 3.1 and 3.2, in the case of pump-level pumping, the pump power that gives the highest optical-to-optical conversion efficiency is the maximum pump power in both experiments and theory, and the optical-to-optical conversion efficiency at that time is 75.8% in theory and 75.2% in the experiments, a difference of only 0.6% points. On the other hand, in the case of direct pumping, the highest optical-to-optical conversion efficiency is obtained at the maximum pump power in theory, and it is 77.2%. In contrast, the highest optical-to-optical conversion efficiency obtained in the experiment was at a pump power of about 60% of the maximum pump power, and it is 76.0%. Thus, the optical-to-optical conversion efficiency for direct pumping was theoretically obtained at the highest pump power, but in the experiment it was obtained at a lower pump power, and when the pump power was further increased, the efficiency decreased. Comparing the pump power that achieves the highest efficiency with the efficiency at that time, the discrepancy between experiment and theory is greater for direct pumping than for pump-level pumping. Figures 5 and 6 compare the input–output characteristics between experiment and theory for pump-level pumping and direct pumping, respectively. Figures 5c and 6c also show the dependence of the optical-to-optical conversion efficiency on the incident pump power. The laser beam waist radii for both pump-level pumping in Figure 5 and direct pumping in Figure 6 are fixed in theory at the condition that gives the highest efficiency at maximum pump power, in Figure 2 for pump-level pumping and in Figure 3 for direct pumping (oscillation wavelength 1048 nm, output coupler transmittance 5%). As shown in Figures 5 and 6, the overall trend of the experimental input–output characteristics is relatively similar to the theory, with fixed laser beam waist radii for both pump-level pumping in Figure 5 and direct pumping in Figure 6. However, in the direct pumping experiment shown in Figure 6, the outputs tend to saturate as the pump power approaches its maximum, while no saturation is observed in the theory because the saturation effects are not included in the theory.

The reasons for this experimental saturation are discussed below. First, it can be concluded that the experimental saturation is almost never due to parasitic oscillation for the following reasons. Since the highest efficiencies, which are extremely close to the theoretical results without any parasitic oscillation, are obtained in the case of pump-level pumping, where saturation is hardly observed, it is concluded that there is almost no efficiency reduction due to parasitic oscillation in the case of pump-level pumping. The reason why there is almost no efficiency reduction due to parasitic oscillations even at high pump intensities is the quasi-four-level laser loss of the low and zero pump intensity regions in the gain medium, and this is also an advantage of not using a complex gain medium that combines non-doped and doped gain medium. In addition, since the pump absorption and quantum efficiencies of the direct pumping of Yb:YAG are almost similar to those of pump-level pumping, the gain is also almost similar for the same pump intensity. For this reason, it is difficult to consider that there is a reduction in efficiency due to parasitic oscillations in direct pumping, even though there is almost no reduction in efficiency due to parasitic oscillations in pump-level pumping.

In the case of Yb-based gain media, there are only two groups of energy levels, so it is assumed that there is no decrease in pump efficiency as in excited-state absorption [1–4]. It is also natural for absorption saturation to occur at high pump intensities, but previous theories have assumed that absorption saturation is resolved for both pump-level pumping and direct pumping when laser oscillation occurs [17,20–24]. For this reason, saturation of the input–output characteristics of lasers using Yb-based gain media has generally been attributed to an increase in quasi-four-level laser losses due to the temperature increase of the gain medium caused by pumping or to a deviation from the optimal laser spot radii due to thermo-optic distortion caused by pumping [37–42]. In contrast, in this experiment, the saturation of the input–output characteristics was observed in the case of direct pumping, which has a lower heating efficiency, while little saturation of the input–output characteristics was observed in the case of pump-level pumping, which has a higher heating efficiency. Furthermore, according to the theoretical analysis, the maximum temperature increase of the gain medium is at most about 10 °C [17]. In other words, it cannot be assumed that saturation is due to an increase in quasi-four-level laser losses caused by the temperature increase of the gain medium. In general, the higher the pump intensity, the higher the gain, so the effect of the efficiency reduction caused by the quasi-four-level laser loss is smaller. The efficiency improvement caused by the higher gain is greater than the efficiency reduction caused by the increase in quasi-four-level laser losses due to the increase in pump intensity [17].

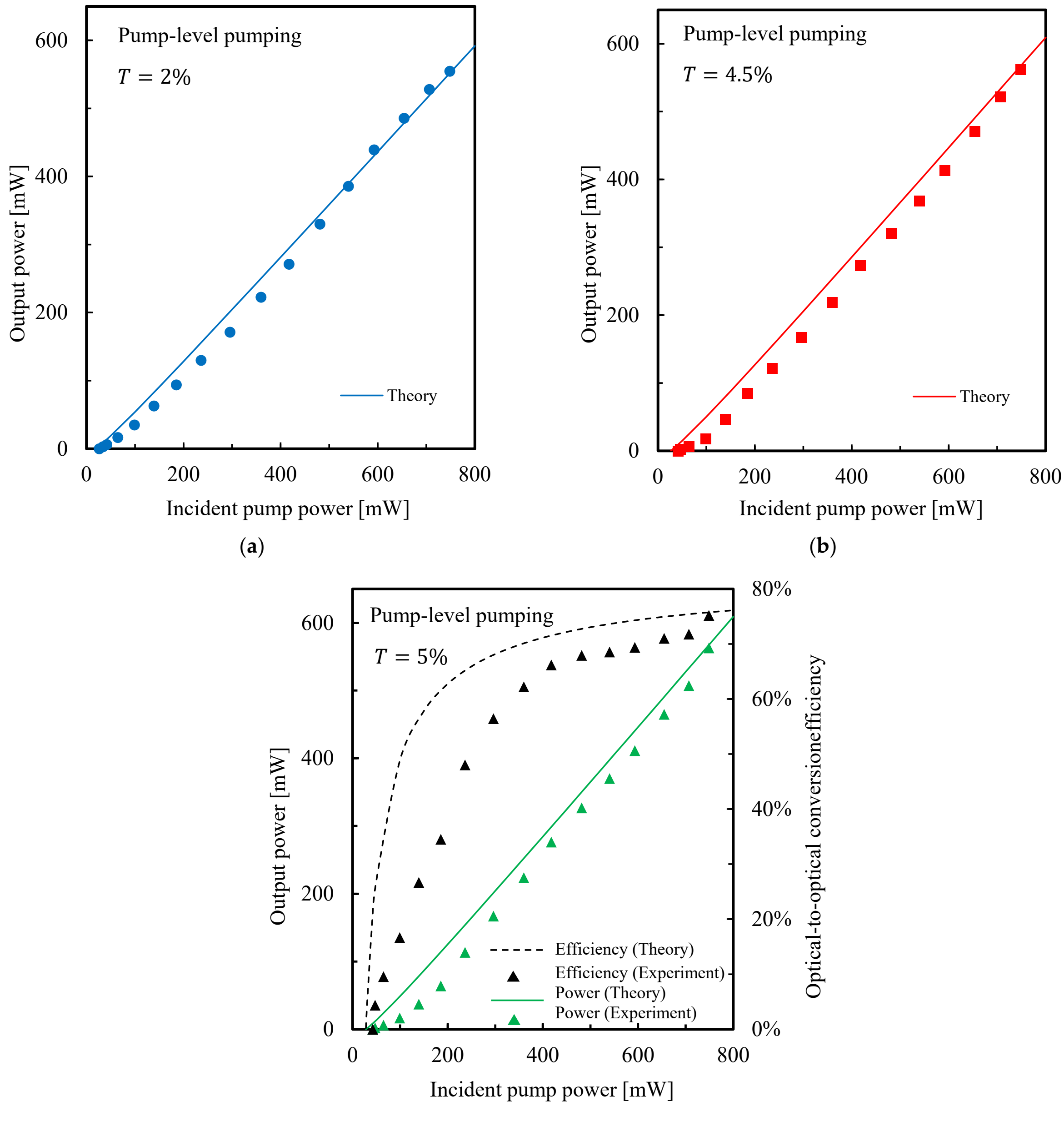


Figure 5. Comparison of experimental and theoretical input–output characteristics for pump-level pumping. The laser beam waist radii in the theory are fixed at the condition where the optical-to-optical conversion efficiency is highest for pump-level pumping at the maximum pump power (the pump power is 750 mW, the oscillation wavelength is 1048 nm, and the output coupler transmittance is 5%). The experimental values of the input–output characteristics are plotted in the same format as in Figure 4. The solid curves show the theoretical input–output characteristics. The colors of the theoretical solid curves correspond to the colors of the experimental results for the same output coupler transmittance. The output coupler transmittance is 2% for (**a**), 4.5% for (**b**), and 5% for (**c**). Also in (**c**), the incident pump power dependence of the optical-to-optical conversion efficiency is shown in black. The black dashed curve shows the theoretical incident pump power dependence of the optical-to-optical conversion efficiency.

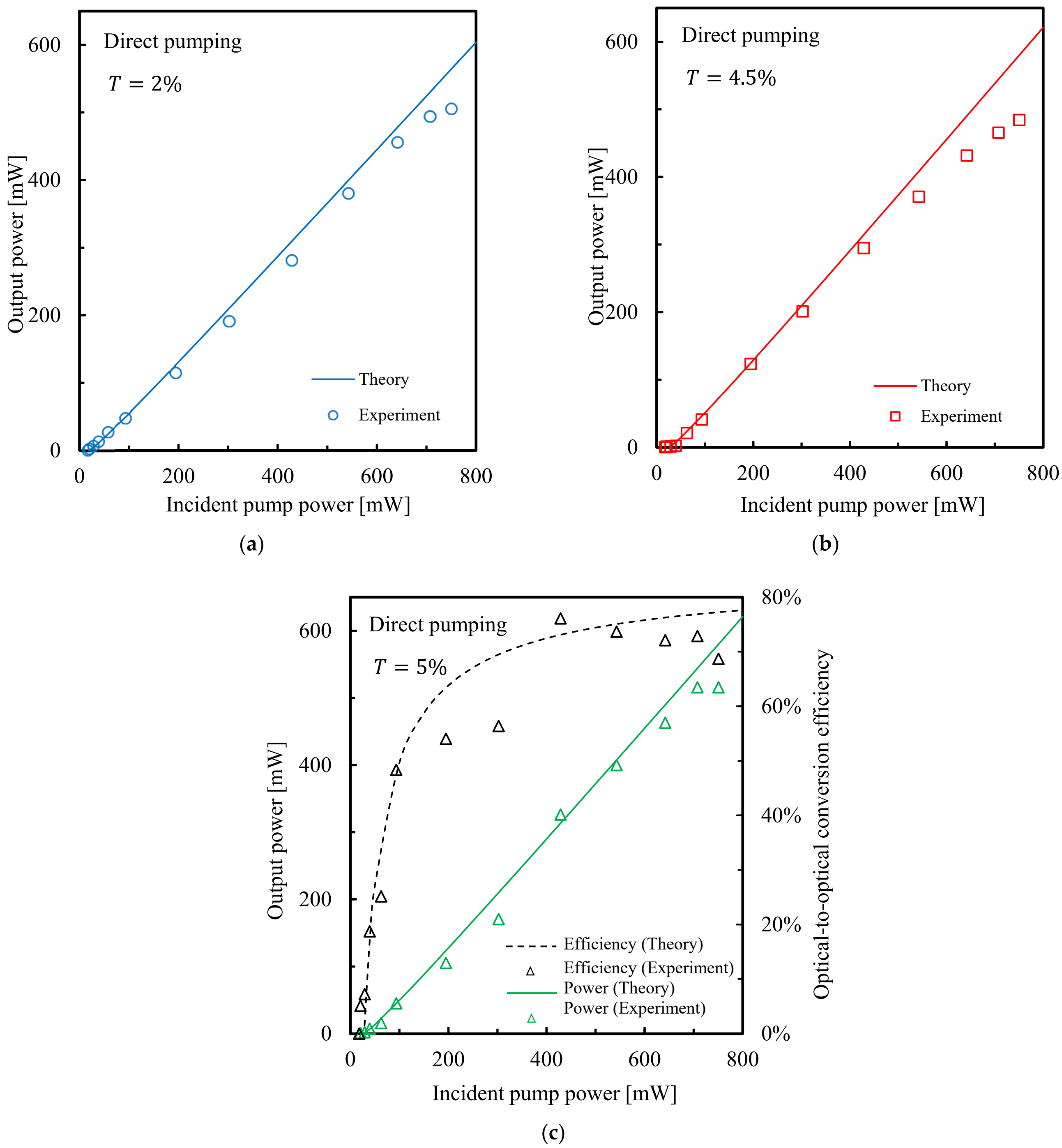


Figure 6. Comparison of experimental and theoretical laser input–output characteristics for direct pumping. The laser beam waist radius in the theory is fixed at the condition where the optical-to-optical conversion efficiency is highest for direct pumping at the maximum pump power (as in Figure 5, the pump power is 750 mW, the oscillation wavelength is 1048 nm, and the output coupler transmittance is 5%). The experimental values are plotted in the same format as in Figures 4 and 5. The theoretical curves are plotted in the same format as Figure 5. The output coupler transmittance is 2% for (**a**), 4.5% for (**b**), and 5% for (**c**). (**c**) also shows the incident pump power dependence of the optical-to-optical conversion efficiency in the same format as Figure 5c.

In this case, the reason for the discrepancy between experiment and theory regarding the input–output characteristics of lasers is often attributed to the fact that the laser beam waist radii are fixed in theory, whereas they vary in experiments due to the fact that the thermo-optic distortion varies with variations in the pump power. This is because the optical-to-optical conversion efficiency is conventionally thought to depend strongly on the geometric overlap between the pump and laser mode distributions, and this is particularly true for quasi-four-level lasers such as Yb-based lasers [4,22–24]. For example, as mentioned in Section 3.1 and shown in Figures 2 and 3, the efficiency in the low-efficiency region, especially at low pump intensities, depends strongly on the laser beam waist radii, which is consistent with the conventional general idea. On the other hand, as also mentioned in Section 3.1 and shown in Figures 2 and 3, the higher the efficiency, especially at high pump intensities, the less the efficiency depends on the laser beam waist radii. The dependence of the efficiency on the spot radii near the maximum efficiency is particularly small the lower the cavity loss and the higher the pump intensity, as shown in particular in Figures 2a,b and 3a,b. The reasons for this are discussed in Section 3.1. This small effect of the geometric overlap on the efficiency means that the effect of the laser alignment and thermo-optic distortion on the efficiency is small at higher pump intensities. This means that high-intensity pumping can achieve a high efficiency with less precise control of the cavity alignment and the effects of thermo-optic distortion on the cavity stability condition, i.e., high-intensity pumping is practical. In other words, the higher the pump intensity, the more difficult it is to attribute the difference between experiment and theory to the difference in laser beam waist radii. In particular, the saturation of the laser output near the maximum pump power in the direct pumping experiment cannot be explained by conventional theories. As explained in Section 3.2, the pump power that gives the most optimized cavity stability conditions and correspondingly optimized laser beam waist radii in this experimental method is the maximum pump power. Also, the region of optimal laser beam waist radii becomes narrower at lower pump powers, but the central values do not vary much, as shown in Figures 2 and 3, for example. Since the laser beam waist radii are optimized for maximum laser output power and efficiency at the maximum pump power, it is impossible to further optimize the laser beam waist radii optimized at the maximum pump power at lower pump powers. In other words, the laser power cannot be considered to saturate due to thermo-optic distortion caused by the pump, and the optical-to-optical conversion efficiency cannot be considered to decrease as the pump power increases.

A final possible reason for the discrepancy between the experimental and theoretical input–output characteristics at higher pump intensities is that the theoretical assumption that the pump absorption saturation is completely resolved by the laser oscillation, mentioned in Section 3.2, may not hold in experiments. In experiments, saturation of the input–output characteristics at high pump intensities is observed for direct pumping rather than for pump-level pumping. In other words, the assumption that the saturation of the pump absorption is completely resolved by the laser oscillation is almost always true for pump-level pumping, but there is a possibility that this is not true for direct pumping at high pump intensities. In general, the distribution of the pump levels is much smaller than that of the upper laser levels. For example, in the case of Yb:YAG at room temperature (20 °C), the ratio of the local Boltzmann distribution of the pump level corresponding to 940 nm to that of the upper laser level is about one-fifth. Therefore, when the distribution of the upper laser level decreases, caused by the balance of the amplified and lost intracavity laser powers in steady-state CW oscillation, i.e., when the gain caused by this distribution is balanced with the cavity loss, the distribution of the pump level decreases to about one-fifth of that of the upper laser level. Therefore, the pump absorption saturation during laser oscillation is easily resolved in the case of pump-level pumping. On the other hand, in the case of direct pumping, the pump level and the upper laser level are naturally the same, so the distribution of the pump level is the same as that of the upper laser level (specifically, about five times that of the pump-level pumping of Yb:YAG), but in the same steady-state CW oscillation, the gain caused by this distribution is also balanced by the same amount of cavity loss, as in the case of pump-level pumping, so it is difficult to resolve the pump absorption saturation. As the pump intensity increases, the pump absorption saturation also increases, so it is assumed that the difficulty of resolving this absorption saturation also increases. The results of the experiment may indicate that in Yb:YAG, the pump absorption saturation for direct pumping is resolved by laser oscillation up to a pump intensity of about 260 kW/cm^2, which is the maximum and where an almost theoretical efficiency obtained, but that it becomes difficult to resolve at higher pump intensities. Indeed, in the case of direct pumping, there is a possibility that it will be disadvantageous to increase the pump intensity too much. However, if this pump saturation effect is included in the theory, the efficiency of the experimental laser can be predicted more accurately. In this case, it is sufficient to optimize the pump absorption efficiency so that the maximum storage efficiency is obtained under conditions where the pump absorption saturation remains. If this optimization is performed, higher efficiencies can be achieved at even higher pump intensities, thus providing the opportunity to achieve even higher optical-to-optical conversion efficiencies for the incident pump power.

5. Conclusions

In summary, the efficiency of the Yb:YAG laser, which is a hemispherical cavity that can be easily made compact, has been improved by high-intensity pumping. First, it was shown theoretically that the higher the pump intensity and the higher the optical-to-optical conversion efficiency, the smaller the dependence of the optical-to-optical conversion efficiency on the laser beam waist radii. In particular, at the corresponding maximum pump intensity of 450 kW/cm^2, even if the laser beam waist radii deviate about twice from the optimal values, the reduction in efficiency is only a few percentage points. This means that at high pump intensities, sufficiently high efficiencies can be achieved without precise cavity optimization. Therefore, the cost of precise tuning to achieve high efficiency can be reduced by high-intensity pumping. In the experiment, on the one hand, at a pump wavelength of 940 nm, corresponding to pump-level pumping, a maximum optical-to-optical conversion efficiency of 75.2% was obtained at the maximum pump intensity of 450 kW/cm^2. On the other hand, at a pump wavelength of 968 nm, corresponding to direct pumping, a maximum optical-to-optical conversion efficiency of 76.0% was obtained at a pump intensity of 260 kW/cm^2, which is about 60% of the maximum pump intensity. These maximum efficiencies at the corresponding pump intensity are close to the theoretical maximum optical-to-optical conversion efficiency at the corresponding pump intensity based on these experimental conditions, even though the pump mode is slightly off the optimum for high-intensity pumping. The reason why the pump intensity that gives the highest efficiency for direct pumping is only about 60% of the maximum is thought to be because the pump absorption saturation is not resolved when the laser oscillates at a higher pump intensity. However, if the pump absorption efficiency is optimized so that the maximum storage efficiency is obtained under conditions where the pump absorption saturation remains, it is possible to achieve even higher efficiencies. To achieve high efficiency by high-intensity pumping, it is not important to have precise values for the large gain product, small quasi-four-level laser loss, high thermal conductivity, low temperature coefficient of the refractive index, and low linear expansion coefficient of the gain material, which were previously considered important for achieving high efficiency. In addition, high efficiency was achieved even with pump-level pumping, where the importance of wavelength stability and the narrowing of the pump source is less than that of direct pumping. Although no complex gain medium combining non-doped and doped gain medium is used, there is almost no efficiency reduction due to parasitic oscillations, despite the high pump intensities. Therefore, these results demonstrate the high practicality of high-intensity pumping and its potential to be a game changer in high-efficiency laser technology. I have checked and revised.

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