Optimization of Intracavity-Doubled Nd:YVO₄ Lasers End-Pumped by High-Brightness Laser Diodes

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(Received August 27, 1998)

In this paper, we report the results of analytical and experimental studies of the characteristics of a high-brightness laser-diode end-pumped Nd:YVO₄/KTP laser. A simple model was developed to optimize the cavity parameters and to estimate the green output power of intracavity-frequency-doubled lasers. Using a 1-W high-brightness laser-diode as the pump source, high-efficiency operation was realized based on the optimized cavity design. The second-harmonic output power at 532 nm was measured to be 286.5 mW at an incident pump power of 881.4 mW, corresponding to an optical-to-optical efficiency of 32.5 %.

Key Words: Intracavity-doubled, Nd:YVO₄, High-brightness laser-diode

1. Introduction

Laser-diode (LD)-pumped solid-state lasers in the visible spectral region are efficient, compact, and robust light sources for various applications such as laser displays and optical data storage. For LD-pumped low- and medium-power CW lasers, intracavity second-harmonic generation (SHG) is a promising approach for frequency doubling because the power densities within the cavity are high and high conversion efficiencies can therefore be realized. As a gain medium suitable for low- and medium-power lasers, Nd:YVO₄ has attracted much attention because of its broad absorption bandwidth and high absorption coefficient at the pump wavelength. High-efficiency intracavity-frequency-doubled Nd:YVO₄ lasers have been reported in recent years.¹⁻⁶⁾ Optical efficiencies of 29.2 %, 26.8 %, and 25 % with respect to the pump power have been reported with KTP as the nonlinear crystal.³⁻⁵⁾ Using two fiber-coupled-diode-bars pumping, optical-to-optical efficiency of 30 % and a green output power of > 6 W were obtained with LBO as the intracavity frequency doubler.⁶⁾ High-efficiency intracavity-doubled Nd:LSB lasers have also been reported recently; an optical efficiency of 30 % has been demonstrated using KTP for frequency doubling.^{7,8)} An important characteristic of Nd:LSB is that it has very low losses at 1.06 μm ($< 10^{-4} \text{ cm}^{-1}$), which is of critical importance for realizing a high-efficiency operation of lasers.

In this paper, we report a high-efficiency Nd:YVO₄/KTP green laser pumped by a 1-W high-brightness laser-diode. A simple model was developed to analyze the end-pumped intracavity-frequency-doubled lasers that gives the green output power as a function of the incident pump power, the pump beam size, and the resonator and crystal parameters. Theoretical analysis shows that a small pump beam size is of critical importance for realizing a high-efficiency operation of an intracavity-doubled laser. High-brightness laser-diodes (with an emission area of only $1 \times 50 \mu\text{m}^2$) make it easier to achieve a small pump beam size. High-efficiency operation was realized based on a high pump density

and an optimized cavity design. The second-harmonic output power at 532 nm was measured to be 286.5 mW at an incident pump power of 881.4 mW, corresponding to an optical conversion efficiency of 32.5 % from LD-pumping to the green output.

2. Theoretical Analysis

R. G. Smith has theoretically analyzed intracavity optical Second Harmonic Generation (SHG) from the viewpoint of power intensity and has pointed out that an optimum length of nonlinear crystal exists.⁹⁾ In laser design, it would be more convenient if one could know the direct dependences of the green output power on the cavity parameters and pump power. We consider the combination of Nd:YVO₄ and KTP in a plano-concave cavity, as shown in Fig. 1, where the nonlinear material KTP is put close to Nd:YVO₄. The pump beam and oscillating beam are taken to have Gaussian distributions and to be collinear in the laser crystal. Following the Casperson's analysis,^{10,11)} we assume that the fundamental power intensity in the cavity, $I(z, r, \phi)$, can be described by

$$\frac{dI}{dz} = \frac{g_0 I}{1 + 2IS} - \alpha_c I \quad (1)$$

where α_c is the distributed loss per unit length in the laser crys-

Fig. 1 Experimental setup of the intracavity-doubled Nd:YVO₄ laser end-pumped by a high-brightness laser diode.

tal. The saturation parameter $S = \sigma\tau/\hbar\omega$, which is equals to the reciprocal of the saturation intensity, is multiplied by a factor of 2 to account for saturation in two directions. g_0 is the small signal gain and is given by $g_0 = (2\sigma\tau\alpha_p\lambda_p P_{p0}/\pi\hbar c w_p^2)\exp(-\alpha_p z - 2r^2/w_p^2)$.

Integrating (1) over the beam cross section yields

$$\frac{dP_c}{dz} = \int_0^{2\pi} \int_0^\infty \frac{g_0 I}{1+2IS} r dr d\varphi - \alpha_c P_c \quad (2)$$

In the end-pump configurations, we assume that the pump and cavity mode spot sizes are constant in the gain medium if the crystal length or the absorption depth is small in the cases of optically thick laser medium like Nd:YVO₄ and Nd:GdVO₄ etc. Equation (2) can then be written in the following simplified form:

$$\frac{dP_c}{dz} \approx \left[\frac{2\sigma\tau\lambda_p P_{p0}}{\pi\hbar c (w_p^2 + w_c^2)} \frac{\alpha_p \exp(-\alpha_p z)}{1+4S\xi P_c/\pi w_c^2} - \alpha_c \right] P_c \quad (3)$$

where w_p and w_c are the pump and cavity mode beam radii in the gain medium, respectively. w_p can be measured directly, and w_c can be calculated from the ABCD law. α_p is the absorption coefficient of the laser crystal at the pump wavelength, P_{p0} is the incident pump power at the input mirror of the laser. $\xi = 1 - 0.92w_p^2/(w_c^2 + w_p^2)$ is a factor obtained by simulating the numerical integration results. Calculation shows that this approximation is accurate to within 7 % for $w_c \geq w_p$.

Using the approximation of low single-pass gain, the round-trip power gain can be obtained by integrating (3) over the laser crystal length l and multiplying by a factor of 2:

$$\Delta P = 2 \left[\frac{2\sigma\tau\lambda_p P_{p0}}{\pi\hbar c (w_p^2 + w_c^2)} \frac{1 - e^{-\alpha_p l}}{1+4S\xi P_c/\pi w_c^2} - \alpha_c l \right] P_c \quad (4)$$

The round-trip nonlinear loss of the cavity, which is the sum of the SHG power in the forward and backward directions, can be described by

$$P_{SHG} = \frac{K P_c^2}{\pi w_c^2} \quad (5)$$

where

$$K = 4 \frac{w_c^2}{w_n^2} \left(\frac{\mu_0}{\epsilon_0} \right)^{1/2} \frac{\omega^2 d_{eff}^2 l_n^2}{n^3 c^2} \quad (6)$$

l_n , n and d_{eff} are the length, refractive index, and effective nonlinear coefficient of KTP, respectively, ω is the radian frequency, and w_n is the beam radius in the nonlinear crystal. If the Rayleigh range, z_0 , of the cavity beam is larger than the KTP length l_n , w_n is almost constant within KTP and can be replaced by w_c . In cases where $z_0 \leq l_n$, however, the intensity reduction of the fundamental light in KTP has to be taken into account.

The fundamental circulating power P_c within the cavity can be evaluated in the steady state by equating the round-trip gain to the sum of the round-trip linear and nonlinear losses of the laser. This gives

$$4KS\xi \left(\frac{P_c}{\pi w_c^2} \right)^2 + (4\delta S\xi + K) \frac{P_c}{\pi w_c^2} + (\delta - 2G) = 0 \quad (7)$$

where

$$G = \frac{2\sigma\tau\lambda_p P_{p0} (1 - e^{-\alpha_p l})}{\pi\hbar c (w_p^2 + w_c^2)} \quad (8)$$

δ is the total round-trip linear loss of the cavity, which can be

written in the form of $\delta = \delta_0 + 2\alpha_c l + 2\alpha_n l_n$, where δ_0 includes transmission losses at the two cavity mirrors and scattering losses at the interfaces, and α_n is the absorption coefficient of KTP at the fundamental wavelength. $P_{p0}(1 - e^{-\alpha_p l})$ on the right-hand side of equation (8) is the absorbed pump power. Equations (5) and (7) give the output SHG power as a function of the pump power and pump beam size, the cavity parameters, and the laser and nonlinear crystal parameters. This model can be used to optimize the resonators and to estimate the green output power of intracavity-doubled lasers.

In intracavity-doubled lasers, the cavity beam size in the nonlinear crystal should be small enough to enhance the fundamental power intensity and SHG conversion efficiency. At the same time, however, the cavity mode size in the laser crystal should be best matched to the pump beam size for increasing the conversion efficiency from the pump to the fundamental power. Therefore, the optimum mode size for the high-efficiency operation of a laser is expected when the two needs are balanced. Figure 2 shows the green output power as a function of the cavity beam waist for several values of pump-beam size at a pump power of 500 mW. It can be seen that the maximum green power is obtained when the cavity mode is best matched to the pump. For a pump-beam waist of 50 μm , for example, the best cavity mode waist is 40 μm , which is smaller than the pump beam. For the same pump beam, the corresponding optimum cavity mode size of a fundamental laser (1.06 μm) with a $T = 5\%$ output coupler, however, was calculated to be about 90 μm using the same model. That is to say, the mode-matching concept of intracavity-doubled lasers is different from that of fundamental lasers. Figure 2 also shows that, at a constant pump power, the conversion efficiency improves with a reduction in pump-beam size. The parameters used in the calculation are as follows: The effective nonlinear coefficient of KTP $d_{eff} = 3.2 \times 10^{-12} \text{ mV}^{-1}$, the refractive index $n = 1.83$, $\omega = 1.78 \times 10^{15} \text{ s}^{-1}$, the fluorescent lifetime and stimulated emission cross-section of Nd:YVO₄ are $\tau = 90 \mu\text{s}$ and $\sigma = 10.0 \times 10^{-19} \text{ cm}^2$, respectively.

KTP length selection is an important topic in intracavity-doubled lasers. The output power as a function of KTP length is shown in Fig.3 for different w_p . It can be seen that there exists an optimum KTP length, for which the maximum output power is obtained. The "optimum length" of KTP depends on the pump (and therefore the cavity)-beam size. At a pump power of 500

Fig.2 Green output power is shown as a function of the cavity beam waist for several values of w_p at a pump power of 500 mW and a KTP length of 5 mm.

Fig.3 Green output power is shown as a function of KTP length for several values of w_p , the pump power is 500 mW and the cavity modes are best matched to the pump.

mW, the corresponding optimum values of KTP length for $w_p = 40, 50$, and $60 \mu\text{m}$ are 3.6, 4.1 and 4.6 mm, respectively. The absorption coefficient of KTP at $1.06 \mu\text{m}$, α_m , was taken to be $5 \times 10^{-3} \text{ cm}^{-1}$ in this calculation. Figure 3 also shows that, at a certain pump power, the output power is higher and the optimum length of KTP is shorter for the pump beam with smaller w_p . Another conclusion that can be drawn from Fig.3 is that the effect of KTP length on the output power is not very sensitive around the optimum values. The curves in Fig.4 show the optimum length of KTP to be a function of pump power; we can also see that l_{op} is a function of the pump power.

Cavity loss, δ , is an important parameter affecting the output of an intracavity-doubled laser. Figure 5 shows the green output power as a function of the incident pump power for different cavity losses. At a pump power of 700 mW, the green output decreased from 216 mW to 110 mW as the cavity loss increased from 0.1 % to 0.9 %.

3. Experimental Results and Discussion

The pump source used in the experiment was a high-brightness LD (Mitsui Petrochemical Industries, LTD. MLD100) with

Fig.4 Optimum KTP length is shown as a function of the pump power for several values of w_p .

Fig.5 Theoretical green output power versus incident pump power and cavity loss.

an emission area of $1 \times 50 \mu\text{m}^2$, maximum output power of 1 W, and an electrical to optical efficiency of 41.5 %. The emission spectrum, as shown in Fig.6, was measured with an ANDO AQ-6315A optical spectrum analyzer at a resolution of 0.05 nm for operation at 20°C and 1 W; the linewidth is $\sim 0.9 \text{ nm}$ (FWHM) centered at 807.2 nm, which is much narrower than that of conventional LDs of 2-3 nm. The light from the diode laser was collimated and focused by a pair of 8-mm focal-length lenses, and the spot size was measured to be about $65 \mu\text{m} \times 70 \mu\text{m}$. The full divergence angle of the focused beam was measured to be 6.7° and 46° in two directions, these values are similar to the divergence angles of ordinary LDs. The small pump-spot size was obtained based on the small emission area of the laser diode, but not at the cost of increasing the divergence angle of the pump beam. The 1 % Nd-doped laser crystal has a thickness of 1 mm and an absorption coefficient of 30 cm^{-1} at the pump wavelength. One side of the laser crystal was anti-reflection-coated at a pump wavelength of 808 nm ($R < 5\%$), high-reflection coated at both the fundamental wavelength of $1.06 \mu\text{m}$ ($R > 99.8\%$) and the second harmonic wavelength ($R > 99\%$) to act as a cavity mirror of the laser (input mirror), and the other side was anti-reflection coated at $1.06 \mu\text{m}$. A 5-mm thick type-II phase-matched KTP was located close to Nd:YVO₄ for intracavity fre-

Fig.6 Emission spectrum of the high-brightness laser diode operating at 20°C and 1 W.

quency doubling. The KTP crystal was anti-reflection coated at $1.06\ \mu\text{m}$ to reduce the passive loss of the cavity; the absorption coefficient of KTP at $1.06\ \mu\text{m}$ is $\sim 5 \times 10^{-3}\ \text{cm}^{-1}$. The output mirror had a radius of curvature of 100 mm and was high-reflective coated at the fundamental wavelength ($R > 99.9\%$) and anti-reflective coated at the green wavelength ($T > 95\%$). It should be noted that although the input mirror of the laser had a high-reflection coating of $R > 99\%$ at the 532-nm wavelength, the reflectivity was measured to be about 70 % for the green light incident on Nd:YVO₄ from the right-hand side because of its scattering and absorption losses.

The round-trip linear loss of the resonator without the intracavity KTP was measured using three output couplers of different transmission T . For the 3 %, 5 % and 10 % mirrors of transmission, the corresponding slope efficiencies are 54.0 %, 56.7 %, and 58.8 %, respectively. The loss is estimated to be about 0.004 from the formula $1/\eta_s = 1/\eta_{s0} + (\delta/\eta_{s0})(1/T)$, where η_{s0} is the limiting slope efficiency. The maximum $1.06\ \mu\text{m}$ output power of 495 mW was obtained at a pump power of 881.4 mW from the 5 % output coupler, corresponding to an optical conversion efficiency of 56.2 %.

The dependence of the green output power on the cavity length was investigated. In Fig.7 we show the experimental results measured at a constant pump power of 300 mW. At medium cavity length, around 50 mm for example, the cavity mode diameter is estimated to be about 260 μm . This size is too large compared with the optimum value of about 75 μm (for a $\sim 70\text{-}\mu\text{m}$ pumping beam), and hence the conversion efficiency is low. The cavity modes are better matched to the pump beam at long and short cavity lengths, and hence higher conversion efficiencies are obtained.

According to the theoretical analysis, we measured input-output characteristics at a cavity length of $\sim 10\ \text{cm}$. The experimental and theoretical results are shown in Fig.8. The laser cavity was first carefully optimized at a pump power of 500 mW by adjusting the positions of Nd:YVO₄ and the output mirror along the optical axis. The maximum second-harmonic output power at 532 nm reached 286.5 mW at an incident pump power of 881.4 mW, corresponding to an "optical-to-optical" efficiency of 32.5 %. Compared with the fundamental optical efficiency of 56 %, the conversion efficiency from the fundamental to the second

Fig.7 Green output power as a function of the cavity length at a pump power of 300 mW, the KTP length is 5 mm and the radius of curvature of the output mirror is 100 mm.

Fig.8 Green output power and the theoretically predicted values as a function of the incident pump power.

harmonic was estimated to be 58 %. The beam-quality parameters M^2 of the green light were measured to be $M^2 = 1.1$ perpendicular and $M^2 = 1.2$ parallel to the c-axis of Nd:YVO₄. The amplitude fluctuations of the green output, which have been referred to as the green problem,¹²⁾ was measured to be better than 5 % using a photodiode. The power stability was measured to be better than 2 % with a power meter over 1 hour of operation.

4. Conclusion

In conclusion, a simple model was developed to optimize the cavity parameters and estimate the green output power of LD longitudinal pumped intracavity frequency doubled lasers. Mode matching and the effects of other parameters on the intracavity doubled lasers, such as pump beam size, cavity loss and KTP length etc, have been discussed. Our analyses shown that small pump beam size (or, high pump density) is important for improving the optical efficiency and shortening the optimum KTP length of intracavity-doubled lasers. Using a 1 W high brightness LD as the pump source, we demonstrate a high efficiency Nd:YVO₄/KTP green laser, the green output power reached 286.5 mW at an incident pump power of 881.4 mW, corresponding to an optical to optical efficiency of 32.5 %.

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