Investigation of Fiber-Coupled Laser-Diode-Pumped NYAB Green Laser Performance

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***Abstract*— The optimum pump condition for a fiber-coupled diode end-pumped NYAB laser has been determined by including the effect of pump beam quality into the analysis. Under the optimum pump condition, 67 mW of the green laser output corresponding to a conversion efficiency 10.3% was obtained from a self frequency-doubling NYAB crystal when pumped by a 650 mW fiber-coupled laser diode. The prospect of higher conversion efficiency is also discussed.**

I. INTRODUCTION

LASER DIODE pumped solid state lasers with green or blue output have been shown to be suitable for applications in laser medicine, high-density optical storage, color display, and optical testing. Recently, a large number of papers on diode-pumped green and blue output solid state lasers have been published [1], [2]. The simplest way of second harmonic generation would be the use of self-doubling laser materials [3], [4]. Compared with the traditional intracavity-doubling designs of gain medium plus nonlinear crystals, these lasers are more compact, affordable, and reliable.

Among the various self-frequency-doubling crystals, neodymium yttrium aluminum borate (NYAB) has a number of desirable features that make it an attractive material for a diode pumped compact green laser system. The self-frequency-doubling cw NYAB laser end-pumped by a diode-laser has been realized in several laboratories [5]–[7]. The conversion efficiency never exceeded 3% in these investigations.

In this letter we demonstrate a high efficient fiber-coupled diode end-pumped NYAB laser. Under the optimum pump condition, 67 mW of the green laser output corresponding to a conversion efficiency 10.3% was obtained from a self frequency-doubling NYAB crystal when pumped by a 650 mW fiber-coupled laser diode.

II. THEORETICAL ANALYSIS

Several theoretical descriptions of self-frequency-doubling cw laser operation have been proposed [8], [9], but the optimum pump condition for maximizing laser output efficiency was not discussed in these investigations. Recently [10], we have included the absorption effect of second harmonic beam into the space-dependent rate equation analysis. Under the steady-state condition and using the plane wave approximation, we have derived a formula relating the second harmonic output to the pump power by including the effect of pump beam quality into the analysis:

$$P_2 = \left[-\frac{B}{2} + \sqrt{\frac{B^2}{4} + \eta_P \eta_0 (P_{\text{in}} - P_{\text{th}})} \right]^2 \tag{1}$$

with

$$B = \frac{2\alpha_i \alpha_2 L \sqrt{\pi \omega_0^2}}{K(1 - e^{-\alpha_2 L})} + \frac{I_{\text{sat}}}{2L} \frac{K(1 - e^{-\alpha_2 L})}{\alpha_2 \sqrt{\pi \omega_0^2}} V_{\text{eff}} \eta_0 \tag{2}$$

$$K = \sqrt{\frac{2^9 \pi^5}{c^3 n_1^2 n_2} v_1 \chi_{\text{eff}}^{(2)}} \tag{3}$$

and

$$P_{\text{th}} = \frac{\alpha_i I_{\text{sat}} V_{\text{eff}}}{\eta_P} \tag{4}$$

where $\eta_P = \eta_t \eta_a (v_1/v_p)$; v_1 is the fundamental laser frequency; v_p is the pump frequency; η_t is the optical transfer efficiency; $\eta_a \approx 1 - \exp(-\alpha L)$ is the absorption efficiency; L is the length of the active medium; n_1 and n_2 are the refractive indexs for fundamental laser beam and second harmonic laser beam, respectively; c is the light velocity in vacuum; a is the absorption coefficient at the pump wavelength; $\chi_{\text{eff}}^{(2)}$ is the nonlinear optical coefficient; α_2 is the absorption coefficient of the active medium at the second harmonic beam wavelength; α_i is the internal-loss coefficient; I_{sat} is the saturation intensity, and ω_0 is the beam waist of the fundamental laser beam. The effective mode volume V_{eff} and the overlapping efficiency η_0 are given by the overlap integrals as [11]

$$V_{\text{eff}} = \left(\iiint s_l(x,y,z) r_p(x,y,z)\, dv \right)^{-1} \tag{5}$$

$$\eta_0 = \frac{\left(\iiint s_l(x,y,z) r_p(x,y,z)\, dv \right)^2}{\iiint s_l^2(x,y,z) r_p(x,y,z)\, dv} \tag{6}$$

where r_p is the normalized spatial distribution of the pump energy, $s_l(x,y,z)$ is the normalized cavity mode intensity distribution.

For a fiber-coupled pump beam, $r_p(x,y,z)$ can be given by [12]

$$r_p(x,y,z) = \frac{2\alpha}{\pi \omega_P^2(z)[1 - \exp(-\alpha L)]} \cdot \exp\left(-2\frac{x^2 + y^2}{\omega_p^2(z)} - \alpha z \right) \tag{7}$$

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TABLE I
THE PARAMETERS FOR NYAB LASER SYSTEM USED IN THE CALCULATION

n_1	1.755	n_2	1.707	σ	10^{-18} cm^2	τ	60 ms
v_1	2.82×10^{14} Hz	v_2	5.64×10^{14} Hz	α	9.2 cm^{-1}	α_2	1.4 cm^{-1}
L	2 mm	α_i	2.8% cm^{-1}	$\chi_{\text{eff}}^{(2)}$	6.83×10^{-9} e.s.u	ω_0	0.13 mm
η_p	= 0.6						

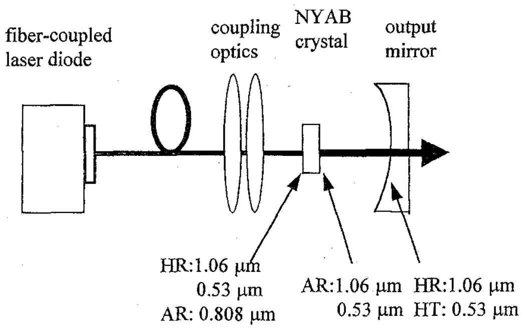

Fig. 1. Fiber-coupled diode pumping experimental setup.

where $\omega_p(z)$ is the pump beam waist in the active medium, and the point $z = 0$ is taken to be at the incident surface of the active medium. On the basis of the paraxial approximation [12], $\omega_p(z) = \omega_{p0} + \theta_p|z - z_0|$. Here, ω_{p0} is the radius at the waist, θ_p and z_0 are the far-field half-angle and focal plane of the pump beam in the active medium. The brightness theorem gives a relationship $n\theta_p\omega_{p0} = C$, where the C is a constant that is a characteristic of the beam quality and n is the refractive index for pump beam. For a fiber-coupled diode, the value of C is easily calculated from its core radius and divergence angle. It can be seen that for small pump beam waists the propagation angles of the beams relative to the optic axis may be too large for good overlap with the resonator mode. Conversely, for small divergence angles the large pump spot sizes may cause a reduction of the mode overlap. The optimum pump spot size for the minimum threshold and the maximum slope efficiency is expected when these two effects are balanced.

Note that in the limit of small $\eta_p\eta_0(P_{\text{in}} - P_{\text{th}})$, i.e., near threshold, (1) can be approximately simplified as $P_2 = [(\eta_p\eta_0/B)(P_{\text{in}} - P_{\text{th}})]^2$. This result shows that the output power increases quadratically with the effective diode laser pumping power for low pump power. On the other hand, in the limit of large $\eta_p\eta_0(P_{\text{in}} - P_{\text{th}})$, (1) can be approximately simplified as $P_2 = \eta_p\eta_0(P_{\text{in}} - P_{\text{th}})$, i.e., the output power increases linearly with the effective diode laser pumping power for high pump power.

III. EXPERIMENTAL RESULTS

We have used a fiber-coupled diode laser to pump NYAB crystal (Lockheed Research Lab., USA) which had been cut at the type I phase-matching angle for second harmonic generation of 1.063 mm ($\theta_m = 32.9°$) with dimension 3 mm × 3 mm × 2 mm. The experimental setup is shown in Fig. 1. The fiber-coupled laser diode is SDL-2362-P2, which has a 50-mm-core fiber of a ~30 deg half width at $1/e^2$ of the peak intensity. The maximum cw output of this diode is 0.7 W. To match the laser wavelength to the absorption peak of NYAB, the emission wavelength of the diode laser is tuned by controlling the operating temperature control system. For 0.808-mm emission, the operating temperature of the diode laser is maintained at about 16.5 °C and the emission wavelength is monitored by a wavemeter during the experiment. The plano-concave configuration of the resonator consists of one planar crystal surface, high-reflection coated at 1.063 mm and 0.532 mm and high-transmission coated at 0.808 mm for the pump light to enter the rod, and a spherical output mirror. The second surface of the crystal is anti-reflection coated at 1.063 mm and 0.532 mm. An ouput mirror with a curvature of 10 cm is used and the reflectivities of the mirror are 99.9% and <10% for 1.063 mm and 0.532 mm, respectively.

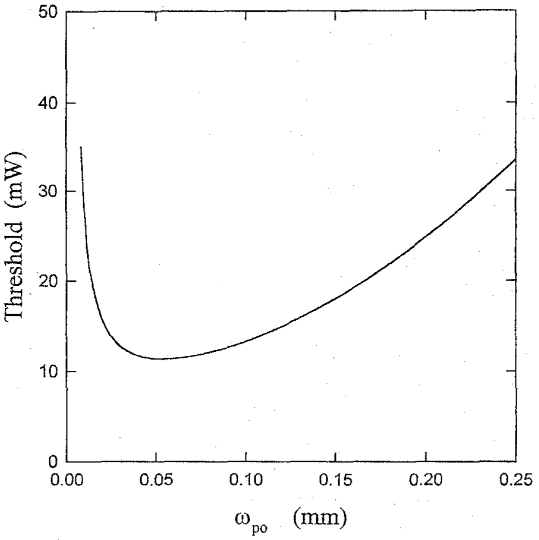

Fig. 2. A plot of calculated threshold pump power as a function of pump beam waists.

Using (1)–(7) and the parameters shown in Table I, we have calculated the threshold pump power as a function of pump beam waists. As is shown in Fig. 2, the threshold has a minimum of approximately 11 mW of pump power with the the pump beam waist around 0.055 mm. To match this optimum pumping condition, the fiber output was focused into the NYAB crystal by using $f = 6.5$-mm focal length collecting lens ($NA = 0.615$), and $f = 14.5$-mm focal length focusing lens ($NA = 0.276$). The pump light can be focused to an about 0.056 mm beam waist in this coupling optics. For comparison, a pair of 8.0-mm focal length ($NA = 0.5$)

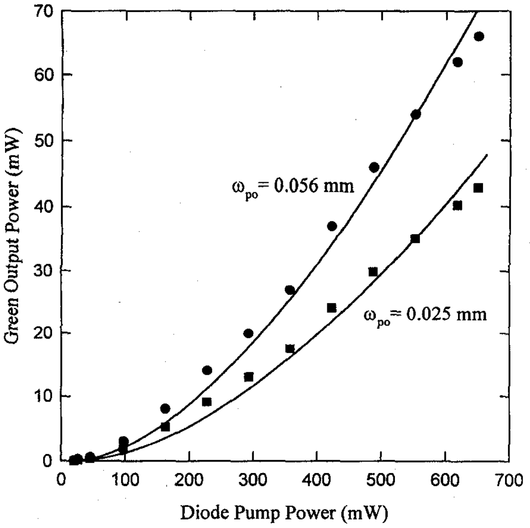

Fig. 3. A plot of experimental (symbols) and theoretical results (solid lines) for output power versus optical pump power.

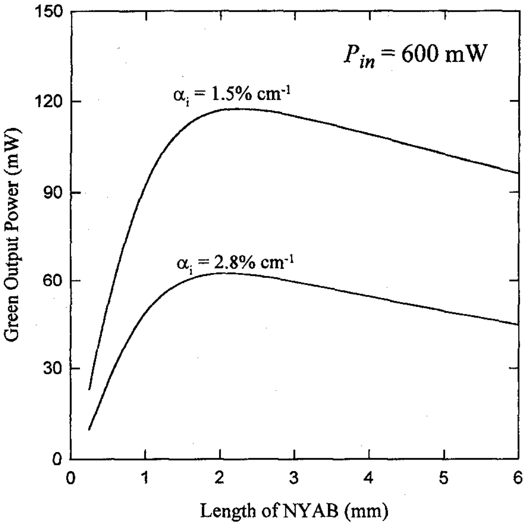

Fig. 4. A plot of the calculated results for the dependence of green output power on the internal losses and the length of the NYAB crystal.

was adopted to produce an about 0.025 mm beam waist. The fiber-coupled diode end-pumped NYAB laser has been operated with these two pumping configurations. Experimental and theoretical results for output power versus optical pump power are displayed in Fig. 3. The 67 mW green output power, corresponding to 650 mW of pump power out of the laser-diode, represents a 10.3% conversion efficiency. Also, it can be seen that the predictions of the analysis (solid lines) agree very well with experimental data (symbols).

With NYAB crystals of good optical quality the efficiency and output power can be improved considerably. The calculation result indicates that reducing the internal losses from 2.8% cm^{-1} to a reasonable value of 1.5% cm^{-1} a pump power of 650 mW may generate the expected output power excessing 120 mW at 0.532 mm, as shown in Fig. 4. The dependence of green output power on the length of the NYAB crystal is also show in this figure. It can be seen that the conversion efficiency can be higher than 20% for a NYAB with internal losses less than 1.5% cm^{-1} under the optimum pump condition. It can be also found that the optimum crystal length is about 1.5–2.0 mm and almost insensitive to internal losses.

IV. CONCLUSION

We have determined the optimum pump condition of a fiber-coupled diode end-pumped NYAB laser by including the pump beam quality into analysis. Under this optimum pump condition, 67 mW of the green laser output corresponding to a conversion efficiency 10.3% was obtained. The conversion efficiency above 20% is predicted for a NYAB crystal with internal losses less than 1.5% cm^{-1} under the optimum pump condition.

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