A 3.5 W Output, Diode-Pumped, Q-switched 532 nm Laser

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ABSTRACT

Three 1O-W fiber-coupled diode lasers were used to pump a single Nd:YAG laser crystal. Average output powers exceeding 11 W of continuous-wave 1064 nm, and 3.5 W of 532-rim at 50 kHz pulse repetition frequency were achieved. An L-shaped cavity which compensated for thermal lensing in the laser crystal was utilized. The Nd:YAG rod and an acousto-optical Q-switcher were located in one arm of the cavity while a frequency-doubler was in the other arm. The 532 nm output beam quality (M2) was 1.5.

INTRODUCTION

Electrically efficient and compact lasers with average output power and pulse repetition frequency of greater than 2 W and 50 kHz, respectively, are needed for laser communication from outer planets to the earth. Single spatial mode beam quality, wavelength in the visible to near infrared range, short (ns level) pulse width, low pulse jitter, and simple thermal management, constitute the other requirements for such a laser. Since with fiber-coupled lasers the diode lasers can be cooled away from the laser resonator, this type of lasers facilitate removal of heat generated by high power diode pump lasers. Other feature provided by fiber-coupled diode lasers are: simpler alignment of the pump laser(s) with the resonator; and reduced complications due to thermal gradients in the laser's mechanical assembly caused by the diode pump lasers. Recently, a number of continuous-wave [1-4] (cw) and pulsed [5-8] solid-state lasers pumped with cw diode lasers have been reported. This paper describes a laser with greater than 11 W of cw output at 1064 nm and 3.5 W of near diffraction-limited 532 nm second harmonic at pulse repetition frequency (PRF) of 50 kHz, with higher efficiency than earlier reports.

A true wall-plug efficiency of 3% was targeted for this laser while efficiencies greater than 10% are desirable. An end-pumped scheme was selected since, generally diffraction-limited output can be obtained more efficiently with end-pumped rather than side-pumped lasers. Properly mode-matched end-pumped lasers can result in near unity quantum efficiency. To avoid the need to generate high voltages for electro-optical Q-switching, an acoustooptical Q-switcher was selected.

DESIGN

Greater than 20 W of 809 nm pump laser power is required to achieve over 2-W of 532 nm average output at pulse repetition frequency of 50 kHz. A pump power level of30 W (the combined output of three 1O-W diodes), used in this experiment, focused to a small diameter, can generate significant thermal-induced lensing and birefringence in most solid-state laser materials. Assuming 30% conversion of the pump power into heat in a Nd:YAG crystal, a pump power absorption of 24 W, and pump spot size (beam radius) of 0.3 mm, a lens with focal length of approximately 10 cm is thermally induced into the crystal.[9] Nd:YAG laser crystal was selected as this laser's active medium since it has lower thermal lensing coefficient than Nd:YV04 and significantly higher thermal fracture strength than Nd:YLF.

To design the laser resonator, the approach proposed by Magni was followed.[10] The radii of curvature of the mirrors were selected such that the resonator supports a single-spatial-mode with large mode volume, has high alignment stability, compensates for the thermally-induced lens, and has low sensitivity to focal length fluctuations of that lens. The resonator was modeled using commercially available software (Paraxia™, Genesse Software). Given the pump laser conditions of 27 W of continuous-wave 809 nm power focused to a spot size of 0.4 ± 0.05 mm in the crystal, two different resonators were identified to satisfy the requirements mentioned above: (1) a piano-concave resonator with the concave mirror having a radius of curvature of 100 cm, (2) a convex-concave resonator consisting of a 12 cm radius of curvature convex mirror and a concave mirror with radius of curvature of 100 cm. The piano-concave mirror was used in this set up due to availability of the mirrors. :,.

EXPERIMENTAL SETUP

A schematic of the folded laser resonator is shown in Fig. 1. With this resonator configuration, the green intracavity beam is confined to a region of the cavity containing only the frequency-doubler. This type of resonator has been used earlier for both end-pumped and side-pumped configurations.[11-13] The output beam of each of the three 1O-W fiber-coupled diode lasers (SDL-3450-P5) was partially collimated by an 8.6 mm focal length lens combination (Newport Research, F-L20) to a total beam diameter of 1.8 cm, measured 1 cm away from the lens. The output wavelength of the lasers (at 25°C) ranged from 808 nm to 811 nm. Following the approach by Fan et al[1] 4, the three closely-spaced collimated beams were focused with an efficiency of 90% into one end of the Nd:YAG crystal using a single 2.35 cm focal length aspheric lens (Melles Griot, 01 LAG 115). The pump-spot radius of the focused beam at the laser crystal was 0.43 mm, as measured by a laser beam profiler (Photon Inc.). The anti-reflection (AR) coated Nd:YAG laser crystal

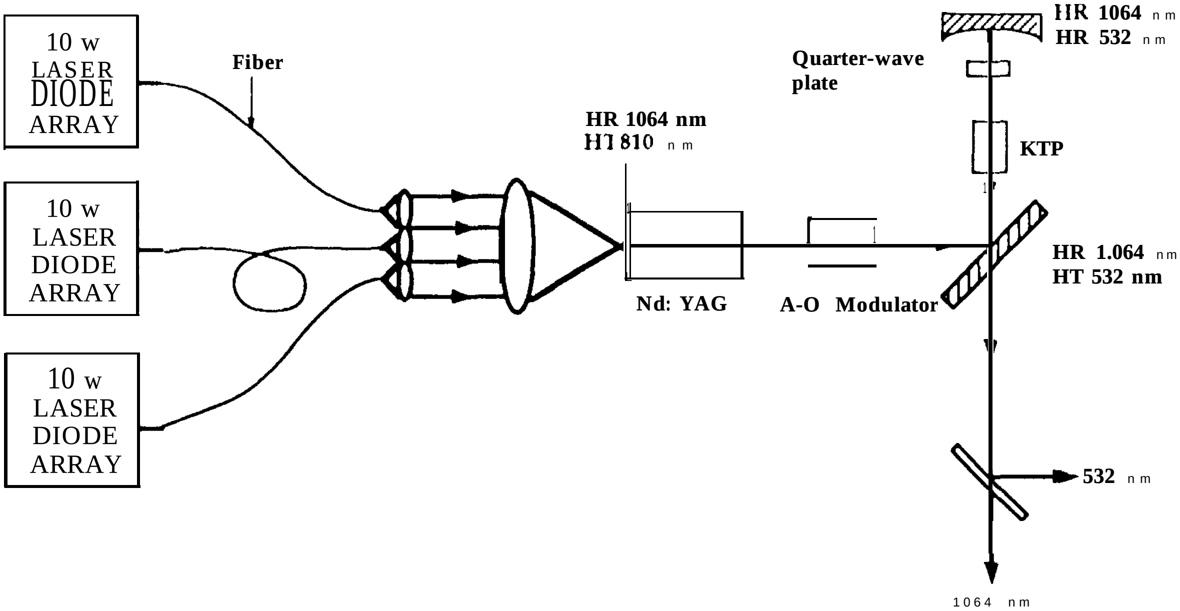

FIG. 1. Schematic of the experimental setup

was 7 mm in diameter with 1 atomic % Nd ion concentration and was 7 mm long. The temperature of the crystal was maintained at 17 ‘C. The input mirror was a 100 cm radius of curvature concave mirror with AR coating at 809 nm on the entrance face, and high reflectance (HR) at 1064 nm on the second surface. The flat fold mirror had a reflectance of 99.9% at 1064 nm for s polarization and transmitted 9270 of the p polarized 532 nm second harmonic at 45° angle of incidence. The flat end mirror had dual HR coating at 1064 nm and 532 nm. The cavity length was 10.5 cm producing a fundamental spot size of approximately 0.52 mm at the input mirror,

Both surfaces of the acousto-optical Q-switcher crystal were AR coated at 1064 nm. It was driven at 80 MHz center frequency with 1,4 W of RF power. A dual-wavelength AR-coated KTP ($KTiPO_4$) crystal was used for frequency-doubling. To avoid gray tracking damage in the KTP crystal[15], the frequency-doubler was not placed at the cavity beam waist. The calculated Gaussian mode spot size in the KTP crystal was approximately 0.185 mm. The second harmonic signal was separated from the residual 1064 nm light with a calibrated dichroic mirror and a band-pass filter located external to the cavity. To measure the 1064 nm laser power, the KTP doubling crystal was removed and the HR-coated end mirror was replaced with a 95% reflectance (at 1064 nm) flat output coupler mirror.

RESULTS

The second harmonic and fundamental average output power, at 50 kHz pulse repetition frequency (PRF), as a function of the incident cw pump power is illustrated in Fig. 2. The threshold for cw 1064 nm and pulsed 532 nm generation, measured at the input mirror of the resonator, were 2.1 W and 2.5 W, respectively. When all three pump lasers operated at the full rated power (10-W each), over 11.7 W of cw 1064 nm power and 3.5 W of 532 nm power were obtained. Approximately 21.1 W, that is 78% of the total pump power was absorbed in the laser crystal. The optical-to-optical conversion efficiencies were 55% and 16,6% for 1064-nm and 532-nm, respectively.

Fig. 3. shows a plot of the second harmonic average output power and laser pulse width as function of the PRF. The Q-switcher was always operated at above 10 kHz to avoid damage to the resonator optics and intra-cavity elements. Considering all electrical power supplied to the pump diode lasers, the Q-switcher, and those for heat removal from diode lasers and laser crystal, the wall-plug efficiency for this laser was 2.3%.

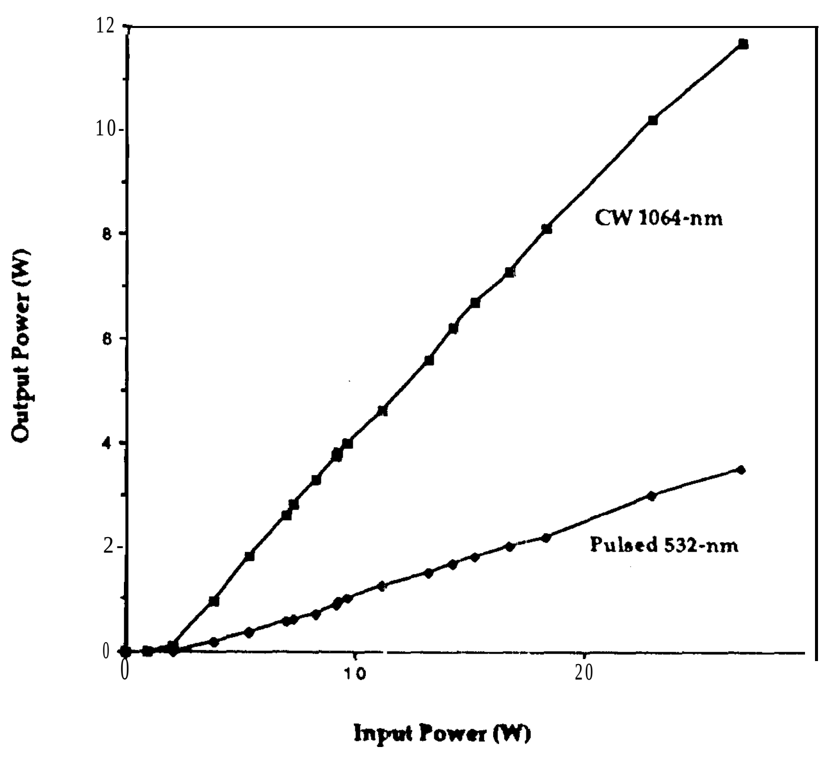

FIG. 2. Continuous-wave output power at 1064 nm and pulsed 532 nm output as a function of the incident pump power.

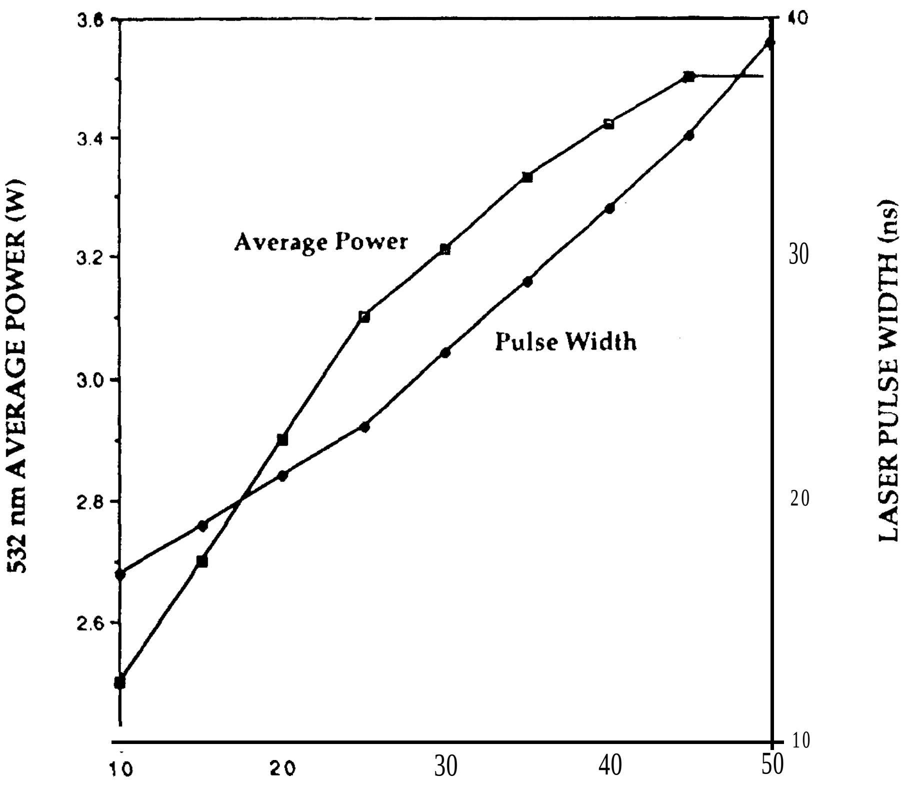

Fig. 3. Average output power at 532 nm and laser pulse width as a function of the Q-switch pulse repetition frequency.

At 50 kHz PRF, The measured pulse-to-pulse energy instability for the 1064 nm output was 4,170 at 50 kHz and greater than 23% at 75 kHz PRF. The increase in pulse-to-pulse instability and pulse width (52 ns at 62 kHz) at higher pulse repetition frequencies is due to reduced gain.

The ratio of the far-field beam diameter to the diffraction limited beam diameter, calculated for the same cavity waist, provides a measure of laser output beam quality (M2 factor).16 The diameter of the beam was measured 2.5 meters from the output coupler, while the laser was operating at full output power. The beam quality was a function of the pump power since the focal length of the thermally induced lens, and therefore the Fresnel number for the cavity, varied with pump power. The measured cw 1064 nm beam divergence was 3.6 mrad, and the diameter of the beam waist was 0.41 mm yielding a beam quality factor of 2.2. The Q-switched 532 nm output beam quality was approximately 1.5 times the diffraction limit.

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REFERENCES:

1) S.C. Tidwell, J.F. Seamans, and M.S. Bowers, Opt. Lett., 18, 116 (1993),

2) Y. Kenada, M. Oka, H. Massuda, and S. Kubota, Opt. Lett., 17, 1003 (1992).

3) M.S. Keirstead and T.M. Baer, in *Digest of conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 1991, paper CFC3.

4) L. Marshall, A. Katz, and H I. Verdun, in *Digest of* conference *on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 1993, paper CMF5.

5) H, Hemmati and J.R. Lesh, IEEE J. Quantum. Electron., 28, 1018 (1992).

6) H. Plaessmann, S. A. Ré, J.J. Alonis, D. Vecht, and W.M. Grossman, Opt. Lett., 18,1420 (1993)

7) A.J.W. Brown, R. Mead, and W.R. Bosenberg, in *Digest of conference on Lasers and Electro-Optics* (Optical Society of America, Washington, DC, 1993, paper CMF7.

8) D.C. Shannon and R.W. Wallace, Opt. Lett., 16,318 (1991).

9) M. E. Innocenzi, H.T. Yura, C.L. Fincher, and R. A. Fields, Appl. Phys. Lett., 56,1831 (1990).

10) V. Magni, Appl. Optics, 25,107 (1986).

11) T.E. Dimmick, Opt. Lett., 14,677 (1989).

12) F. Hanson and D. Haddok, Appl. Optics, 27,80 (1988).

13) I.L. Bass and R.W. Presta, in Proc. SPIE, 1040,116 (1989).

14) T. Y. Fan, A. Sanchez, and W.E. DeFeo, Opt. Lett., *14,105’* (1991).

15) J.C. Jacco, D.R. Rockafellow, and E.A. Teppo, Opt. Lett., 16,1307 (1991).

16) A.E. Siegman, in SPIE Proc., 1224,1 (1990).