

Harmonic generation at high repetition rate with Q-switched Nd:YVO₄ lasers

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ABSTRACT

A variety of applications require short, energetic laser pulses delivered at high repetition rate. These include micro-machining, range finding, and scientific applications such as amplifier pumping. An important advantage provided by diode-end-pumping of solid state lasers is that this type of geometry allows the generation of short, energetic, Q-switched pulses at high repetition rate. The high peak power of such pulses facilitates harmonic generation. In this paper, we describe a high average power, high repetition rate Q-switched Nd:YVO₄ laser, pumped by a fiber-coupled diode bar [1]. The laser provides pulses of excellent spatial quality at repetition rates up to 100 kHz, average power 3-4 W, and durations of 8 to 20 nsec. The near-diffraction-limited beam and the high peak power allow efficient harmonic generation at high repetition rates. Second harmonic generation is achieved in non-critically-phase-matched LBO with a conversion efficiency of 55% at 20 kHz, providing an average power of 1.75 W at 532 nm. Third harmonic generation (to 355 nm) in LBO has been achieved with >20% efficiency, resulting in an ultraviolet average power of 0.65 W at 20 kHz.

1. CHOICE OF GAIN MEDIUM

Nd:YVO₄ offers some advantages over traditional hosts for diode pumped systems, including a high absorption coefficient at the pump wavelength and a large stimulated emission cross section at the laser wavelength. In an end-pumped Q-switched laser, the large stimulated emission cross section and high inversion density provide a very high gain, resulting in short Q-switched pulse durations even at high repetition rates. The pulse energies at high repetition rate are higher than can be achieved with more traditional hosts, due to a short upper state lifetime that allows a fast recovery of the excited state population. The fast recovery also enhances the pulse to pulse stability of the laser at high rates. However, this same short lifetime (~100 μsec) limits the energy storage capability

of the medium at low repetition rates. For example, given ~ 10 W of diode bar pump power, the maximum pulse energy achieved at low repetition rate (~ 200 μ J) with an end-pumped Nd:YVO₄ laser is about 0.25 of that achieved with an Nd:YLF laser (~ 800 μ J) in a tightly folded resonator (TFR) configuration [2]. This can be attributed to the fact that the upper state lifetime in Nd:YLF is significantly longer (~ 500 μ sec). In contrast, at repetition rates higher than 10 kHz, we observe comparable pulse energies with either Nd:YVO₄ or Nd:YLF. However, pulse durations obtained at repetition rates over 10 kHz are typically significantly shorter with Nd:YVO₄ based resonators, owing to the very high stimulated emission cross section ($\sim 15 \times 10^{-19}$ cm² vs. $\sim 1.8 \times 10^{-19}$ cm² for Nd:YLF).

2. FIBER-COUPLED DIODE-BAR PUMP SOURCE

The fiber-bundle-coupled, diode-bar pump source used to end-pump this laser has been described elsewhere [1,3,4]. It is comprised of a collimated 10 or 20 W, multi-element diode bar, coupled into a fiber optic bundle. The output end of the bundle is ~ 1 mm in diameter, with a numerical aperture of ~ 0.15 . Approximately 85% of the collimated diode pump light is emitted by the bundle and is subsequently imaged into the gain medium through a dichroic end mirror.

3. LASER HEAD DESIGN

Short, energetic pulses of high spatial quality are desirable for efficient harmonic conversion. For a given small signal gain, the shortest Q-switched pulsed durations correspond to short cavity lifetimes, and therefore short cavity lengths. However, the TEM₀₀ mode size also depends upon cavity length, and we find that short cavities (~ 5 cm) tend to oscillate with multiple spatial modes and therefore degraded beam quality. Cavity lengths of ~ 10 cm provide a compromise between the shortest achievable pulse durations and TEM₀₀ operation. A schematic of the 2 mirror laser design is shown in Figure 1. The M² values achieved with this resonator are on the order of 1.1 and the beam profiles are fit very well with gaussian profiles. We measure the beam profiles with a slot scanner, and measure M² by measuring the beam size as it propagates into and out of a waist that is generated by an extracavity lens. For a given waist size, the ratio of the ideal Rayleigh range to the measured Rayleigh range is taken as M² value for the beam.

We use an acousto-optic SF-10 Q-switch that has been optimized for high diffraction efficiency and a fast rise time. The loss that can be induced by such a Q-switch

is not as high as can be achieved with an electro-optic device, but the SF-10 Q-switch was found to provide adequate suppression of oscillation in the high gain Nd:YVO₄ laser.

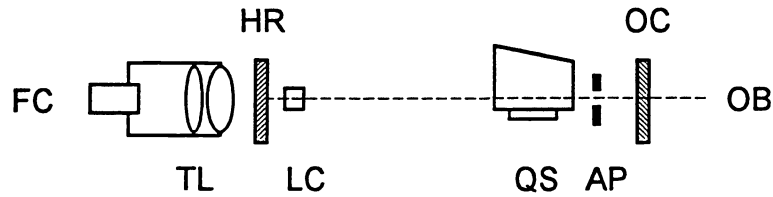


Fig. 1. Q-switched laser head schematic. FC = fiber connector, TL = telescope lenses, HR = high reflector, LC = laser crystal, QS = Q-switch, AP = aperture, OC = output coupler, OB = output beam.

Additionally, the use of a RF-driven acousto-optic device is critical for certain OEM applications, since driving requirements are simplified and very compact geometries are possible. The laser head package dimensions are approximately 6 x 2 x 2 in³. The compact, simple design provides excellent pointing stability; typical pointing drift over a 30 minute period is on the order of 5 μ rad.

4. SYSTEM PERFORMANCE AT 1.064 μ m AND HARMONICS

Typically output pulse energies and pulse durations are plotted as a function of repetition rate in Fig. 2. In Fig. 3, peak power and average power are plotted as a function of repetition rate. The "knee" in the average power curve occurs at approximately 20 kHz. At higher rates, the average power approaches the maximum CW power that can be generated by the laser (3 - 4 W).

The unique combination of nearly-diffraction-limited beam quality ($M^2 < 1.2$) with high peak power (10-30 kW) is ideal for harmonic generation, even at high repetition rates (>10 kHz). Non-critically-phase-matched lithium triborate (NCPM LBO) is used for type I second harmonic generation. This material is as an excellent alternative to KTP; no evidence of gray tracking is observed in this material even at multiple watt power levels. An additional important advantage is the large acceptance angle afforded by the non-critical phase matching; the frequency doubled output beam preserves the beam quality of the fundamental input beam with negligible change to M^2 , ellipticity, or astigmatism. We focussed the 1064 nm beam to a $\sim 70 \mu$ m radius in a 12 mm long piece of NCPM LBO

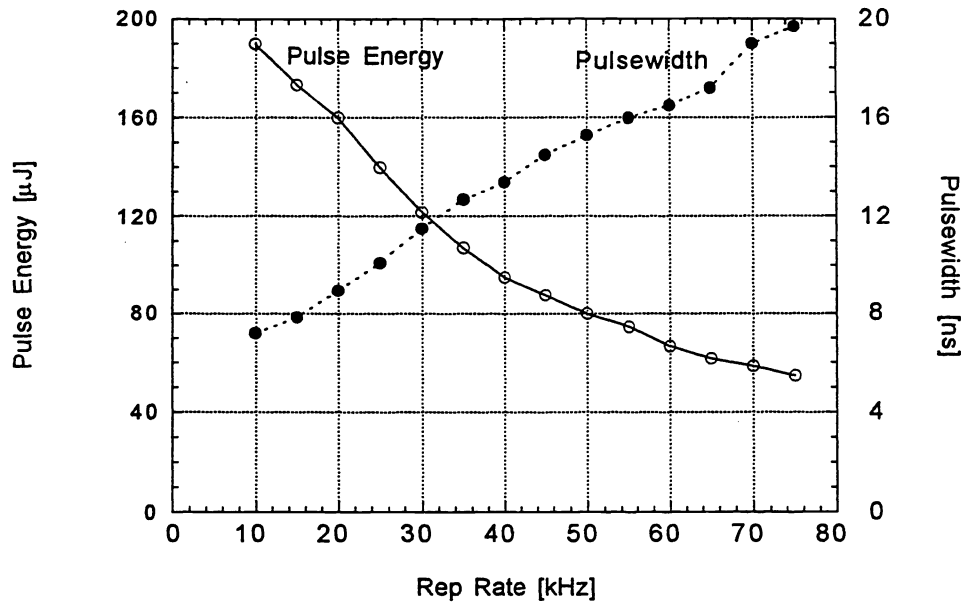


Fig. 2. Pulse energy and pulse width as a function of repetition rate at 1.064 μm .

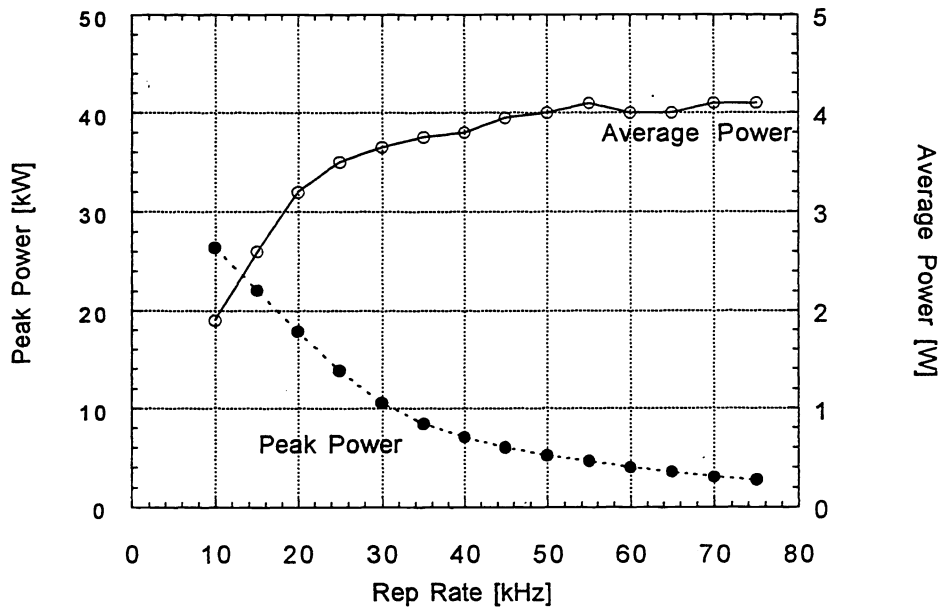


Fig. 3. Peak power and average power as a function of pulsewidth at 1.064 μm .

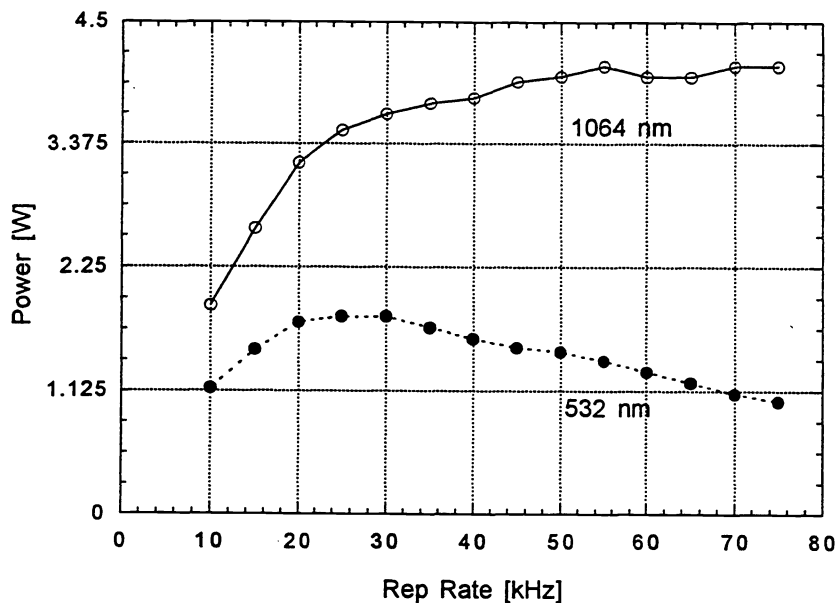


Fig. 4. SHG average power at 0.532 μm as a function of repetition rate.

that was temperature stabilized at ~ 155 $^{\circ}\text{C}$. Conversion efficiencies of $\sim 55\%$ were achieved at a repetition rate of 20 kHz, resulting in 1.75 W (85 μJ) at 532 nm of excellent spatial quality and pulse energy stability. Figure 4 depicts the average power at 532 nm as a function of repetition rate. In a related experiment, third harmonic generation in LBO provided 0.65 W at $>20\%$ conversion efficiency from the fundamental power to 355 nm, also at 20 kHz. The third, fourth, and fifth harmonic generation performance will be presented elsewhere [5].

In conclusion, we have demonstrated that diode-pumped Nd:YVO₄ lasers are suitable sources for the generation of harmonics at high repetition rate. The excellent spatial quality and short pulse durations have allowed us to generate 1.75 W at 532 nm at 20 kHz with $\sim 55\%$ efficiency. Third harmonic generation efficiency is also high with this source ($> 20\%$ at 20 kHz, with ~ 0.65 W output). The compactness and simplicity of the fiber-bundle-coupled diode-bar pump source and end-pumped Nd:YVO₄ head provide excellent pointing, energy, and power stability in OEM environments.

5. REFERENCES

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