

# Diode pumped 1kHz high power Nd:YAG laser with excellent beam quality

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## ABSTRACT

The design and operation of a one kilohertz diode pumped all solid-state Nd:YAG master oscillator power amplifier system with a phase conjugate mirror is presented. The setup allows high power scaling without reduction in beam quality.

**Keywords:** solid-state lasers, Nd:YAG, diode pumping, phase conjugation, stimulated Brillouin scattering, pulse amplification, Q-switching, beam quality

## 1. INTRODUCTION

In recent years high power diode pumped all solid state lasers have emerged as viable sources of high brightness radiation. Both cw and high repetition rate pulsed sources are increasingly becoming available due to the increased availability and decreasing costs of the pump diodes. Diode pumping combines many technological advantages over lamp pumping such as reduced heat load in the laser crystals, resulting in better beam quality, smaller size requirements allowing a more compact design, higher efficiency, longer lifetimes resulting in less maintenance and downtime, and better stability, resulting in less output noise and fluctuation. At NCLR a high repetition rate all solid-state tunable laser system is under development for use in spectroscopy and advanced materials processing. This system is of the master oscillator power amplifier (MOPA) type and consists of a Q-switched single mode ring zigzag slab Nd:YAG master oscillator and a 4-pass Nd:YAG zigzag slab power amplifier. In order to preserve the excellent beam quality of the oscillator, stimulated Brillouin scattering phase conjugate reflection is employed after the second pass through the amplifier. The design and operation of this system is described in this paper. In the next sections each of the components in our system and overall system performance will be discussed in detail.

## 2. OSCILLATOR

Previously we reported on a standing wave oscillator with either a brick shaped or a Brewster angled Nd:YAG slab.<sup>1</sup> The oscillator crystal was pumped with a 5-bar quasi-CW diode array from Spectra Diode Labs. The duration of the pump pulse was  $200\mu s$  at maximum current. The  $2 \times 2 \times 20mm^3$  Nd:YAG-slab was mounted in the vertical plane between two copper blocks for cooling. The slab dimensions were chosen for optimal side pumping and mode volume control, with Brewster-angle faces for low-loss transmission without coatings. The linear cooling geometry caused thermally induced astigmatism which could be partially compensated for with

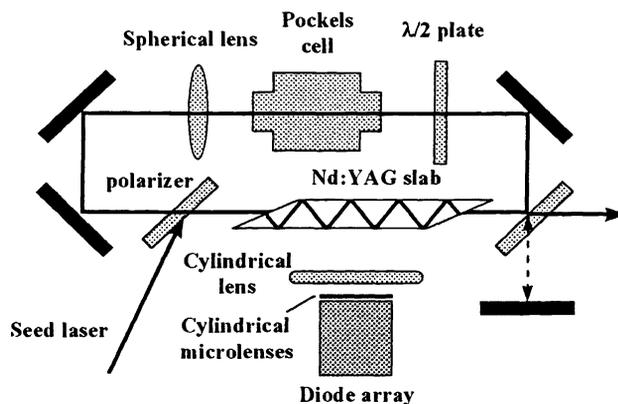


Figure 1: Schematic of the oscillator

cylindrical intracavity optics. However non-cylindrical aberrations and depolarization eventually limited the output of this oscillator and the maximum repetition rate in Q-switched mode. An improved oscillator involving a zigzag slab to compensate for thermal lensing and depolarization was therefore designed similar to the cw oscillator of Shine *et al.*<sup>2</sup> A 16-bounce, 1.8 by 1.7mm cross section, 1% Nd:YAG Brewster angle crystal was used with a total pumped length of 28mm. The non-TIR faces were clamped between gold-coated specularly reflecting glass plates to avoid coolant flow along these surfaces. Teflon coatings were used to insulate the total internal reflection (TIR) faces from coolant water turbulence and shield the O-rings from radiation. In Q-switched mode small diffractive light losses which spilled over the edges of the slab were a problem in that they would burn the O-rings due to the high intensity. This would result in an absorbing layer of carbonized rubber on the teflon coating which if left unattended would eventually damage the slab surfaces. A gold leaf coating has been applied to alleviate this problem. In the previous standing wave cavity design single longitudinal mode (SLM) operation was achieved by seeding with a commercial cw single mode Nd:YAG laser and a home built locking scheme. Due to the polarizing Brewster end faces twister mode operation in that cavity was impossible and spatial hole burning reduced the SLM output energy to approx. 85% of the unseeded value. Therefore it was decided to operate the current oscillator in a ring cavity mode. This reduces round trip gain with respect to output coupling but improves extraction efficiency. Output coupling was optimized following Degnan,<sup>3</sup> with some slight modifications to account for the zigzag slab amplifying medium and the ring cavity geometry. Unidirectional lasing in the ring was achieved with an external mirror which during the buildup phase of the pulse would reflect the output in one direction back into the cavity, thereby favoring the opposite direction. Although seeding could also impose unidirectional lasing, the improved stability of the output in long pulse mode and the ease of alignment made this the preferred setup for unidirectionality. The cavity length was approx. 48cm and in order to obtain a stable cavity a  $f = 1.5m$  lens was added. Single transverse operation was monitored with a beam profiler and self-referencing interferometer.<sup>4</sup>

### 3. AMPLIFIER

The amplifier was a commercial odd-bounce zigzag slab amplifier with a rectangular cross section of  $6 \times 3mm^2$ . The slab was pumped over approx. 60mm by an 80-bar diode array with a max. 15% duty cycle. Output from the oscillator was fed through a square aperture which was relay imaged into the amplifier. In the second pass the beam was spatially separated from the first pass and again relay imaged into the amplifier to avoid diffraction

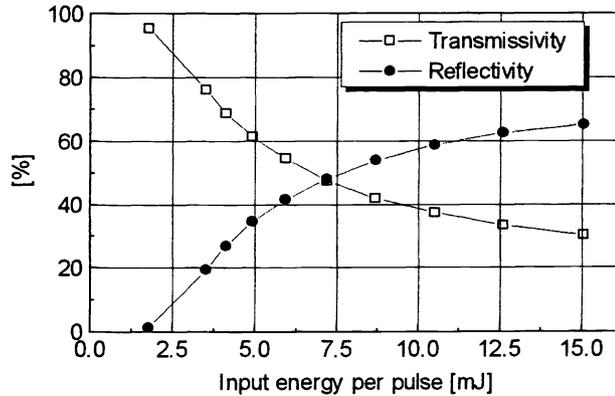


Figure 2: Brillouin reflectivity and transmissivity

losses and possible hot spots in the beam profile. After two passes through the amplifier the beam intensity profile was severely distorted even without pumping. In view of the high pulse energies in 4-pass amplification phase conjugation was essential to correct for these aberrations and thereby avoid amplifier damage. A Faraday isolator separated the overlapping input and output beams from the amplifier. Subsequently the radiation could be used in non-linear optical wavelength conversion schemes.

#### 4. PHASE CONJUGATION

Filtered HPLC-grade Freon-113 was used in the SBS phase conjugator. A MOPA type double cell setup was used to lower the threshold and enhance reflectivity. The incoming square cross section  $3 \times 3 \text{mm}^2$  beam was focused with  $f = 200 \text{mm}$  and  $f = 50 \text{mm}$  lenses into the quartz cells. In Fig.2 the Brillouin reflectivity is shown at a pulse repetition rate of  $400 \text{pps}$  for  $25 \text{ns}$  pulses. Due to the poor beam profile the intensity at the focus is difficult to predict but repeatable phase conjugation with high fidelity could be routinely obtained. Measurements of the beam profile and phase front before and after amplification showed excellent phase front restoration. Even for a double moded input (due to damage on the oscillator slab) the phase conjugation faithfully reproduced the input mode structure.

#### 5. SYSTEM PERFORMANCE

Previously the Brewster angled and brick slab oscillators were limited to operation up to  $400 \text{Hz}$ .<sup>5</sup> The current zigzag slab oscillator allowed operation up to  $1 \text{kHz}$  with pulse energies up to  $3.5 \text{mJ}$ . This relatively low pulse energy was due on the one hand to higher losses in the zigzag slab and on the other hand to a smaller stored energy. For a doubled pumping load the pulse energies increased to  $7.5 \text{mJ}$  but residual thermal lensing and deformation of the slab limited the operation to  $400 \text{Hz}$ . Higher pumping load caused degraded output quality and damage to the  $\text{LiNbO}_3$  Q-switch. Measurements of the amplifier gain showed a cw small signal gain of approx. 3 at maximum diode current. However the pulsed gain was significantly lower due to saturation and possibly transient effects, as shown in Fig.3. At low repetition rate the amplifier pump pulse duration could be extended resulting in an increased gain. At high repetition rate the maximum duty cycle of the amplifier limited

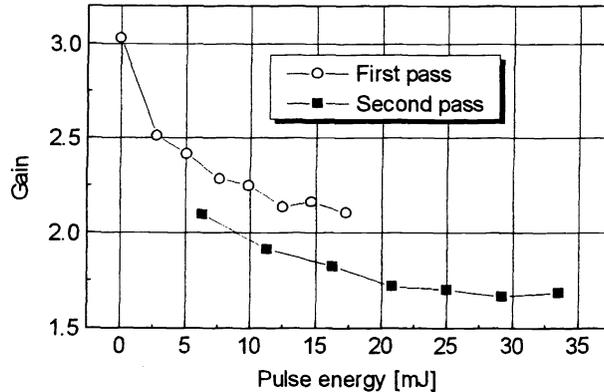


Figure 3: Amplifier gain at 10pps as a function of input energy.

the gain. Due to the non-linear dependence of the SBS reflectivity on the input pulse energy, most efficient 4-pass amplification occurred at 400pps resulting in an output of over 20W. At higher repetition rates the decreased oscillator pulse energy in combination with the limited pump pulse duration in the amplifier limited the efficiency and ultimately the output power. For example at 800pps the average output power had increased to just over 25 Watt. Higher pumping power in the amplifier will further increase the efficiency and result in good SBS reflection at higher repetition rate. Current work is also aiming at improving the thermal management in the oscillator slab which will enable higher oscillator energies and better SBS reflection.

## 6. REFERENCES

- [1] H.P. Godfried, E.A.J.M. Bente, and H.L. Offerhaus, "Single transverse mode, diode pumped Nd:YAG Q-switched oscillator," *OSA Proceedings on Advanced Solid State Lasers*, B.H.T. Chai and S.A. Payne, Eds., Vol. 24, pp. 420-422, Optical Society of America, Washington, DC, 1995.
- [2] R.J. Shine, A.J. Alfrey, R.L. Byer, "40W TEM<sub>00</sub> diode laser pumped Nd:YAG miniature slab laser," *Opt. Lett.*, **20**, 459-461, (1995).
- [3] J.J. Degnan, "Theory of the optimally coupled Q-switched Laser," *IEEE Journal of Quantum Electron.*, **QE-25**, 214-220, (1989).
- [4] C.B. Edwards, P. Lee, and M. Tatarakis, "Single shot wave front measurements of sub-ps laser pulses," *SPIE Proceedings on Beam Control, Diagnostics, Standards, and Propagation*, W. Lindsay, A. Giesen, D.H. Leslie, and H. Weichel, Eds., Vol. 2375, pp. 254-260, SPIE, Bellingham, WA, 1995.
- [5] H.L. Offerhaus, H.P. Godfried, and W.J. Witteman, "All solid state diode pumped Nd:YAG MOPA with stimulated Brillouin phase conjugate mirror," *Opt. Comm.*, **128**, 61-65 (1996).