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250 Watt Average Power Electro-Optically Q-Switched Diode Pumped Power Oscillator

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Abstract
We describe an electro-optically Q-switched, diode-pumped Nd:YAG slab laser *oscillator* operating at an average power of greater than 250 watts. More than 100 watts of frequency doubled light has been demonstrated.

Introduction
The availability of compact and efficient frequency converted solid state lasers with multi-hundred watt average powers could enable the practical deployment of a number of remote detection and ranging technologies, with both civilian and military applications, as well as stimulate solid state laser applications in photochemistry and photolithography. Although several demonstrations of ≈ 100 watts frequency doubled output from solid state laser systems have been reported, they have utilized either master-oscillator/power amplifier configurations, with the unavoidable degree of complexity inherent to that approach,[1,2] or intracavity frequency conversion of acousto-optically Q-switched lasers which gives pulse durations too long for further frequency conversion and range gating.[3] While recent advances in diode pumping technology[4] have made possible very compact (single head) and efficient (≥ 6% electrical to optical) kilowatt average power oscillators, only free lasing operation, with ≈ 100 μs long output pulses and peak powers in the few kilowatts range, has been previously reported.[5,6]

The primary barrier to the demonstration of equally compact *Q-switched* oscillators at these power levels has been the lack of an electro-optic switch capable of reliable operation at the very high average powers which exist inside the cavity of a several hundred watt power oscillator. Until now, simple electro-optically Q-switched power oscillators have been limited to average powers of less than 100 watts. In this paper we report recent experiments which demonstrate that electro-optically Q-switched power oscillators with substantially higher average powers are possible. The fundamental enabling technology for this advance is a thermally robust Q-switch design. Some preliminary frequency conversion results are also presented as direct verification of the short pulse, high peak power output of the Q-switched oscillator.

Laser Cavity
The cavity layout is shown in Figure 1. The diode pumped slab and zigzag optical path were previously described in References 5 and 6. Briefly, a 4 mm x 16 mm aperture, 90 mm long slab of Nd:YAG is pumped through the 16 mm x 90 mm faces by two high average power diode laser arrays.[4] The ends of the slabs are not Brewster tipped. Instead, the entrance face is wedged ≈ 2°, and is antireflection coated. The rear 4 mm x 16 mm face is cut perpendicular to the larger slab faces and is coated as a high reflector. A thin film polarizer was used in reflection mode, and the high reflector was flat to minimize beam divergence in the Q-switch. The output coupler was a 1 m concave, 40% reflector, and the total optical path length was approximately 50 cm.

The three diamond zigzag path and flat face slab configuration greatly reduces thermal lensing and depolarization effects compared to those

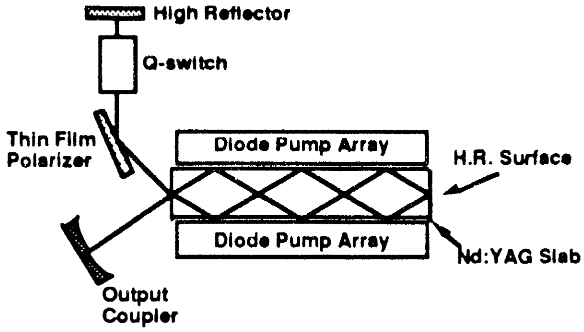

Fig. 1. Cavity configuration for the Q-switched, diode pumped slab laser.

found in YAG rod systems.[5] Nonetheless, under load the slab develops an optical wedge and a mild negative lens in the horizontal (narrow) dimension. As a consequence, it was necessary to re-adjust the cavity alignment to reoptimize the power after each change in drive current. The slab also exhibits noticeable depolarization, primarily near the top and bottom in the vertical (long) dimension as shown in Figure 2. At the highest repetition rate, 2.5 kHz, the integrated depolarization loss at 1.06 μm is approximately 10%.

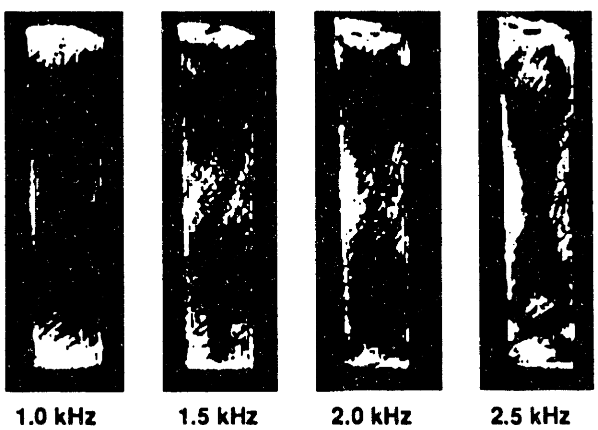

Fig. 2. Depolarization patterns in the diode pumped slab at various repetition rates. Drive current = 140 A, pulse length = 120 μs.

With the stated cavity configuration and the available diode pump arrays, the spatial profile of the fundamental beam is not as uniform as desired. Figure 3 shows the far field pattern we observed during Q-switched operation. We believe that the observed spatial structure arises from the combined effects of pump nonuniformity, residual thermal lensing, and the spatially varying depolarization loss.

Q-switch Design

The two issues of most concern for the operation of an electro-optic Q-switch in a high average power laser cavity are optical damage and thermal depolarization. Previous experience has shown that lithium niobate Q-switches have very low insertion losses, and surface damage thresholds in the 100 MW/cm^2 range for Q-switched pulses. However, thermally induced stress depolarization has prevented the use of single crystal, z axis switches above the ≈ 100 watts laser output level.[6]

Our Q-switch consists of two lithium niobate crystals separated by a quartz 90° polarization rotator, as shown in Figure 4. Each crystal was the standard z axis cut, x field orientation, with 7 mm x 20 mm apertures and 10 mm lengths. The crystals were bonded with an electrically conducting epoxy to precision machined ceramic slabs which were plated with gold electrode pads so that voltage could be applied independently to each crystal. Care was taken to align the two crystals so that the assembly gave a sharp, symmetric isogyre pattern when viewed between crossed polarizers. Subsequently, the quartz rotator was inserted between the crystals and oriented so the entire assembly showed a uniform extinction between parallel polarizers. A more detailed analysis of the characteristics of this compensated electro-optic modulator and a comparison with other compensated designs is in preparation.

Intracavity measurements during free-lase operation (using a 90% reflecting output coupler) implied that this Q-switch could tolerate average one-way intracavity laser powers as high as 700 watts without exhibiting stress depolarization effects.[6] The observed depolarization loss is plotted in Figure 5 as a function of the calculated one-way power. In offline testing, we have observed residual depolarization, apparently due to pyroelectric charging, in some crystals. This effect has been observed previously in lithium niobate Q-switches, although only in situations where the crystals were subject to environmental temperature changes, rather than because of laser beam heating.[7] With this particular Q-switch assembly, we did not observe any depolarization effects which could definitely be ascribed to pyroelectric charging. Nonetheless, care was taken to avoid sudden changes in average power (for example, briefly shutting off the laser) during

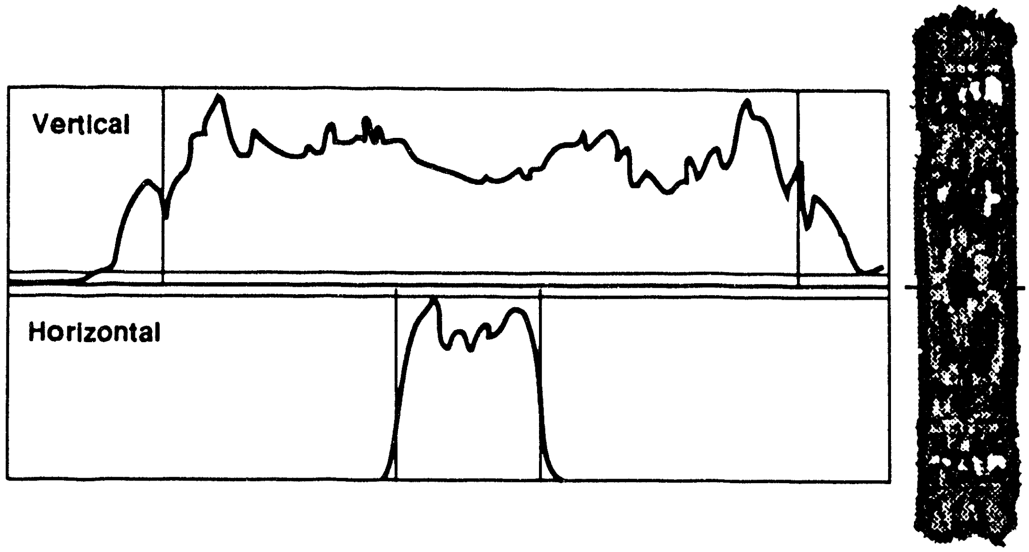

Fig 3. Far field beam profile.

Q-switched operation to prevent pre-lasing, which might lead to optical damage.

The Q-switch was operated in the standard quarter-wave mode with an applied voltage of 2.1 kV for holdoff. The pulser (Fastpulse Technology 8006) dropped the applied voltage to -550 V with a fall time of ≈ 5 ns to Q-switch. The large negative bias was used to overcome the well known piezoelectric clamping effect in lithium niobate.[8]

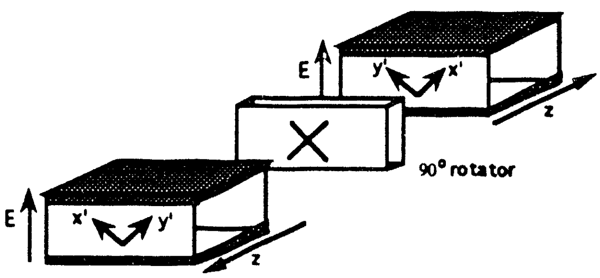

Fig. 4. Q-switch design. The polarity of the crystal z axis and the applied electric field is indicated by the arrows. x' and y' indicate the induced electro-optic birefringence.

Q-switched Laser Performance

In these experiments the laser repetition rate was fixed at 2.5 kHz and the drive current pulse length was fixed at 100 μs. The laser power was varied by changing the diode array drive current. Over the current range of 60–105 A employed in our experiments, the slab single pass gain is estimated to vary from 0.5 Neper to 0.8 Neper. The 40% reflective output coupling mirror was chosen as a compromise between providing sufficient feedback under low gain conditions and minimizing the circulating power (and subsequent thermal load on the Pockels cell). Aside from this consideration, no attempt was made to optimize the output coupler.

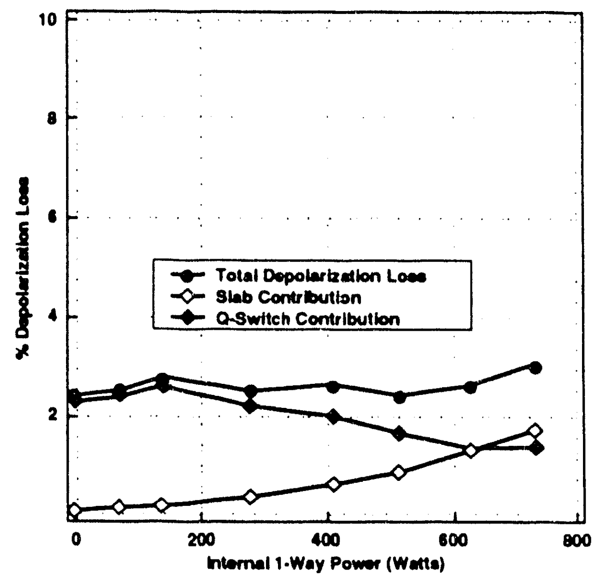

Fig. 5. Q-switch depolarization vs. one-way power observed during free-lasing experiments.

The average power was measured directly with a Laser Precision RT-1000 meter whose detector was placed ≈ 0.5 m from the output coupler to allow the beam to expand to reduce the irradiance on the blackened faceplate. The meter readings were corrected for the factory quoted detector reflectivity at 1.064 μm. The pulse width was measured with a Thorlabs 201 photodiode with a quoted risetime of 1 ns. Figure 6 shows the Q-switched average power and the pulse width as a function of the diode current. Note the rapid decrease in pulse width as the current (hence gain) increases. Figure 7 shows that the observed pulse shape has the typical asymmetric form expected for fast Q-switching. When the Q-switch pulser was switched off, no lasing was observed.

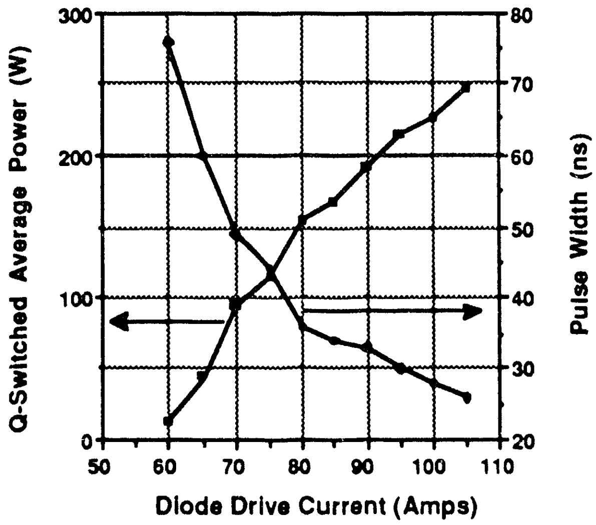

Fig. 6. Q-switched average power (squares) and FWHM pulse width (diamonds) as a function of diode drive current. The pulse repetition rate was 2.5 kHz.

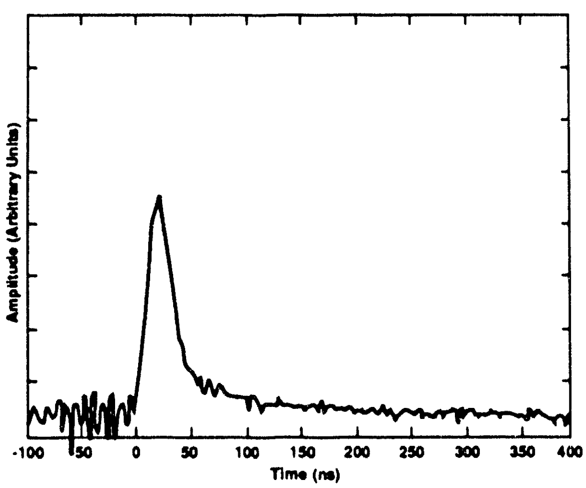

Fig. 7. Q-switched pulse shape at 250 watts output level (26 ns FWHM).

At the highest power level, the internal circulating (2-way) power through the Q-switch is approximately 500 watts (≈ 0.8 kW/cm^2), as estimated from the measured output coupler reflectivity. Similarly, the peak 2-way irradiance at the Q-switch is ≈ 13 MW/cm^2 averaged over the beam size. Although the average irradiance is low relative to lithium niobate's ≈ 100 MW/cm^2 damage threshold, the local irradiance may be as much as two times higher due to the nonuniformity of the laser beam.

Frequency Doubling

For the frequency conversion experiments, the output beam was focused by a single 400 mm focal length lens to a waist size of 4 x 0.8 mm^2. The Rayleigh range was estimated to be approximately 20 mm by translating a beam profiling camera through the waist.

The frequency conversion crystal was a 6 mm long slab of KTP cut for type II doubling of 1.064 μm, whose AR coated entrance and exit faces were 2 mm high and 8 mm wide. The crystal z axis was perpendicular to the 2 mm x 6 mm faces. Water cooled blocks were in contact with the 8 mm x 6 mm faces. The crystal was placed at the beam waist and aligned with the laser in free lasing mode before exposing it to Q-switched light.

The second harmonic power was separated from the residual fundamental by a fused silica holographic beamsplitter which was etched for 0.96% diffraction efficiency at 0.532 μm at an angle of 10°. According to the manufacturer, the characteristics of this optic remain constant up to at least 1 kilowatt of average power. By inserting a calibrated, green blocking, red passing filter in front of the detectors for each power measurement, we ascertained that the 1.064 μm light which is diffracted (in second order) parallel to the second harmonic beam constituted less than 1% of the measured power. We placed separate power meters in both the + and - diffraction paths to monitor the second harmonic and in the zero order (undiffracted) beam which monitored the total power (1.06 + 0.53 μm) transmitted through the frequency doubler. The measured total transmitted power was 10% smaller than the incident power measured separately with the same meter.

At each average power, the phasematching angle was adjusted to maximize the second harmonic signal. Since the pulse width decreases and energy per pulse increases with increasing drive current, we expect the conversion efficiency to **increase** as well, in the absence of thermal dephasing effects caused by the increase in average power. Figure 8 shows that the conversion efficiency does increase roughly linearly with increasing peak power calculated as the energy per pulse divided by the FWHM pulse width. Thus, there is no clear indication that average power induced dephasing effects are causing a rollover in conversion efficiency even at these average powers.

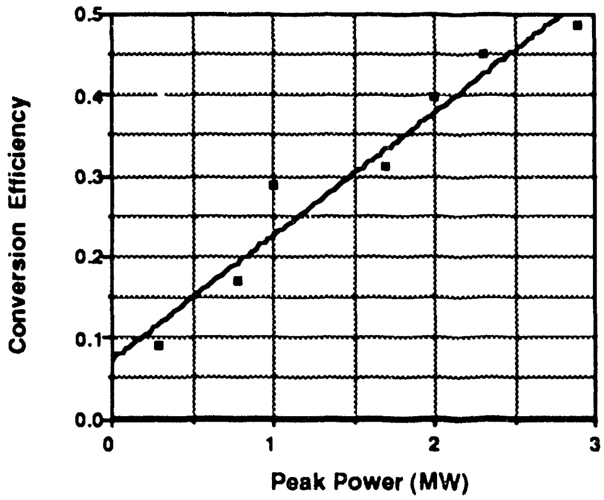

Fig. 8. Conversion efficiency versus peak power, computed as the energy per pulse divided by the FWHM pulse width.

Frequency conversion measurements were made up to a fundamental average power of 210 watts (95 A diode current), generating approximately 103 watts of 0.53 μm light. At this average power the nominal peak power is 2.7 MW (80 mJ, 30 ns), nearly 30 x the nominal "threshold power" figure of merit[9] for KTP. The average irradiance at the maximum current used in the frequency conversion measurements (95 A) was estimated to be 80 MW/cm^2. Using d = 3.2 pm/V for the effective nonlinear coefficient of KTP,[10] the average drive parameter[9] $C^2L^2I = 1.4$. However, the beam profile indicates that the maximum local irradiance could be as much as 2 times higher. In fact, raising the current to 100 A caused the crystal to damage. Assuming that the 0.53 μm absorbence was 0.03 cm^{-1}, a typical value for KTP, and neglecting any 1.064 μm absorbence, we estimate[11] a maximum transverse temperature gradient in the 2 mm direction of less than 3° C at the highest power level.

Concluding Remarks

We have operated the Q-switched slab laser at ≈ 250 watts of average power for several hours without pre-lasing or damage to the Q-switch or ancillary cavity components. There was no indication that the Q-switch was at the limits of its average power performance at the 250 watts level. In addition, we have used the Q-switched beam to frequency double the laser at average power levels of 100 watts for the second harmonic for approximately 30 minutes of operation. At this power level, the conversion efficiency appeared to depend linearly on the peak power with no sign of thermal roll-off. Currently, a major obstacle to substantially higher average power operation for both frequency conversion and Q-switching is the observed beam non-uniformity, which forces us to run at a smaller aperture averaged irradiance (to avoid optical damage) than could be used if the beam were uniform. Therefore, we are currently focusing our efforts on modifications of the laser which will yield an output beam with a more uniform irradiance profile.

Acknowledgments

Helpful conversations with Ron Blachman of Crystal Technology Inc., on the subject of pyroelectric charging and optical damage in lithium niobate are gratefully acknowledged. William Cook was responsible for the design and fabrication of the Q-switch mounting hardware.

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