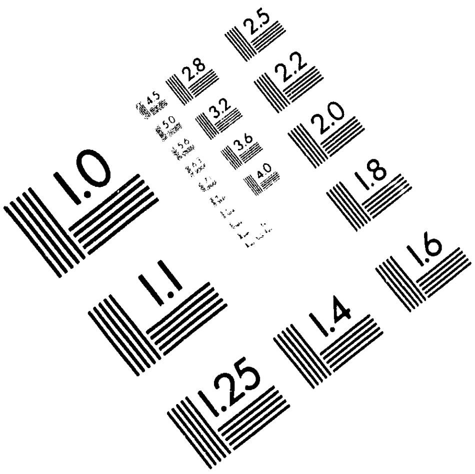

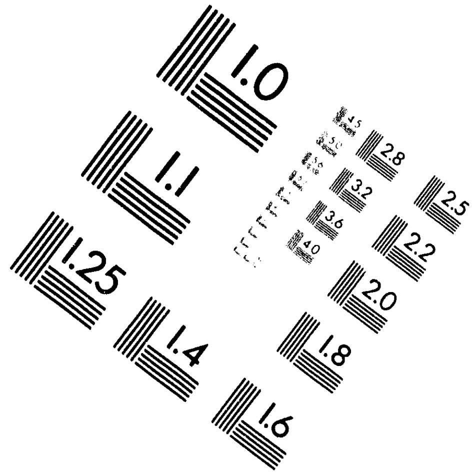

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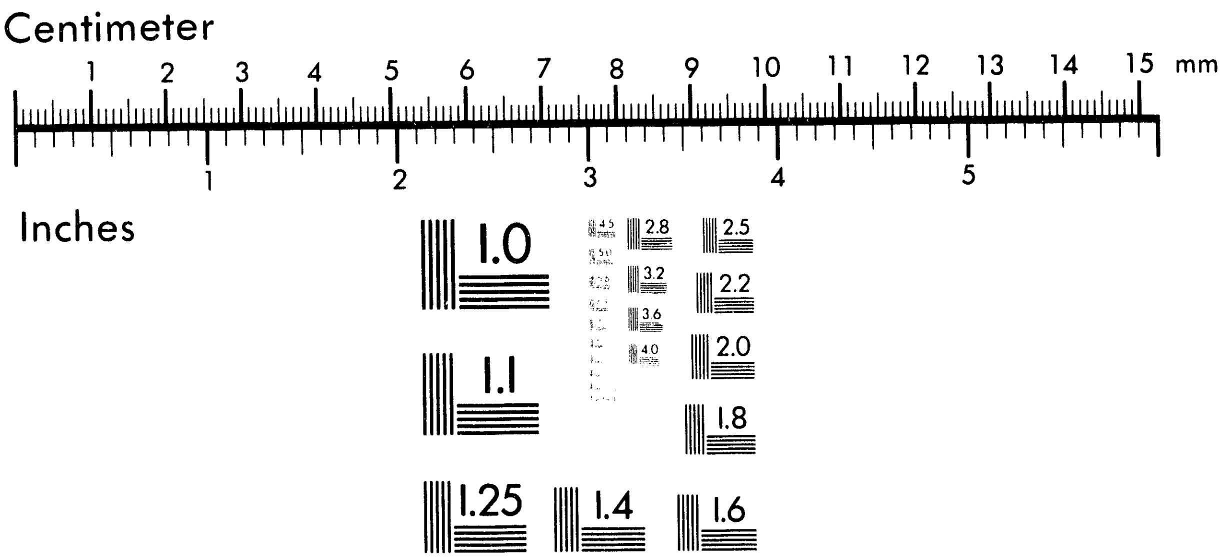

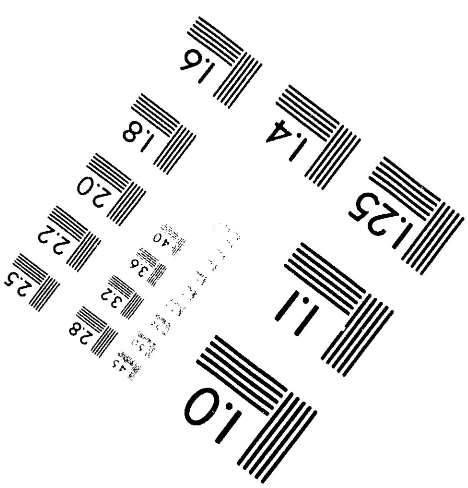

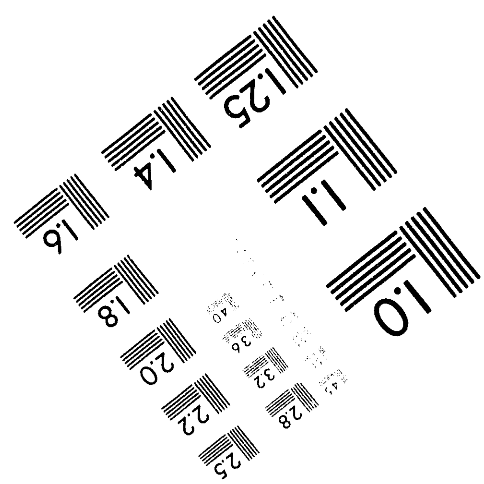

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>100 Watt Average Power at 0.53 μm with 25 ns, 2.5 kHz Repetition Rate Pulses from a Single Power Oscillator

S. P. Velsko, B. Comaskey, G. F. Albrecht, and R. J. Beach

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ABSTRACT

We have generated approximately 100 watts of frequency doubled light from the output of an electro-optically Q-switched, diode-pumped Nd:YAG slab laser *oscillator* operating at an average power of 200 watts (2.5 kHz repetition rate, 80 mJ/pulse, 25 ns pulsewidth). The Q-switch was a compensated z-axis propagation $LiNbO_3$ electro-optic modulator, and the frequency conversion crystal was a thin slab of KTP. In addition, Q-switched operation at an average power of approximately 250 watts with 26 ns pulsewidths has been demonstrated.

1. INTRODUCTION

Compact and efficient frequency converted solid state lasers with multi-hundred watt average powers are highly desirable for a number of industrial and military applications. Previous demonstrations of ≈ 100 watt frequency doubled output from solid state laser systems 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 intracavity average powers which exist inside power oscillators operating at greater 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. The frequency conversion results we report are direct verification of the short pulse, high peak power output of the Q-switched oscillator.

2. LASER CAVITY

The cavity layout is shown in Figure 1. The diode pumped slab and zig-zag optical path have previously been 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.

With the stated cavity configuration and the available diode pump arrays, the spatial profile of the fundamental beam exhibited a nearly 2:1 peak to average variation in irradiance. The output is multi-transverse mode and is assumed to be far from diffraction limited.

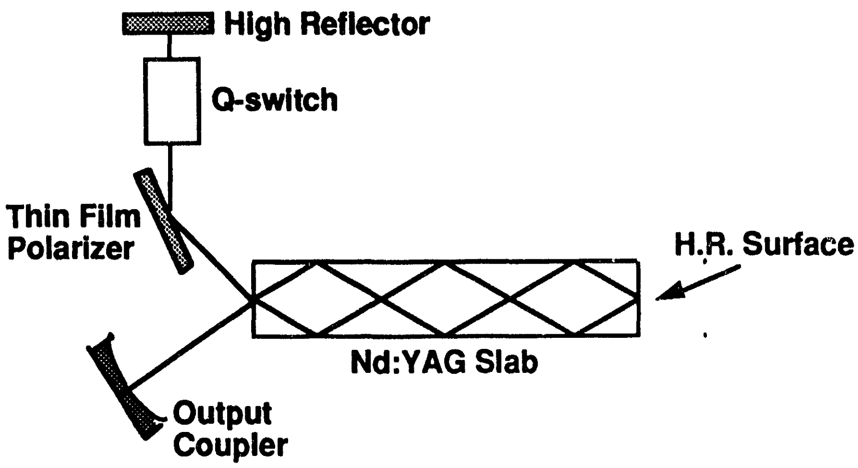

Figure 1. Cavity configuration for the Q-switched diode pumped slab laser.

3. Q-SWITCH DESIGN

The Q-switch utilized in the experiments we report here consists of two lithium niobate crystals separated by a quartz 90° polarization rotator, as shown in Figure 2. Each crystal was the standard z axis cut, x field orientation, with 7 mm x 20 mm apertures and 10 mm lengths.

Both offline testing as well as intracavity measurements during free lase operation implied that this Q-switch could tolerate average laser power densities as high as 3 kW/cm^2 without exhibiting stress depolarization effects.[6] Care was taken to avoid sudden changes in average power (for example, briefly shutting off the laser) during Q-switched operation to prevent pyroelectric charge induced depolarization which might cause pre-lasing.[7]

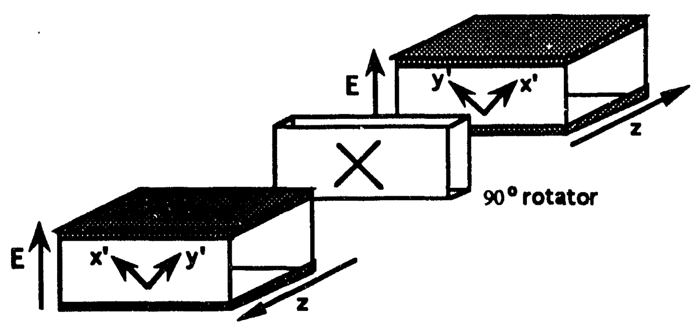

Figure 2. Q-switch design. The polarity of the crystal z axis and the applied electric field is indicated by the arrows. x' and y' indicate the induced electro-optic birefringence.

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]

4. Q-SWITCHED LASER PERFORMANCE

In these experiments the laser repetition rate was fixed at 2.5 kHz and the diode drive current pulse length was fixed at 100 μs. The laser power was varied by changing the diode array drive current. The 40% reflective output coupling mirror was chosen as a compromise between providing sufficient feedback under low gain conditions (< 1 Neper single pass), 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.

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 pulsewidth was measured with a Thorlabs 201 photodiode with a quoted risetime of 1 ns. The pulses had the typical asymmetric form expected for fast Q-switching but were otherwise featureless. Figure 3 shows the Q-switched average power and the pulse width as a function of the diode current.

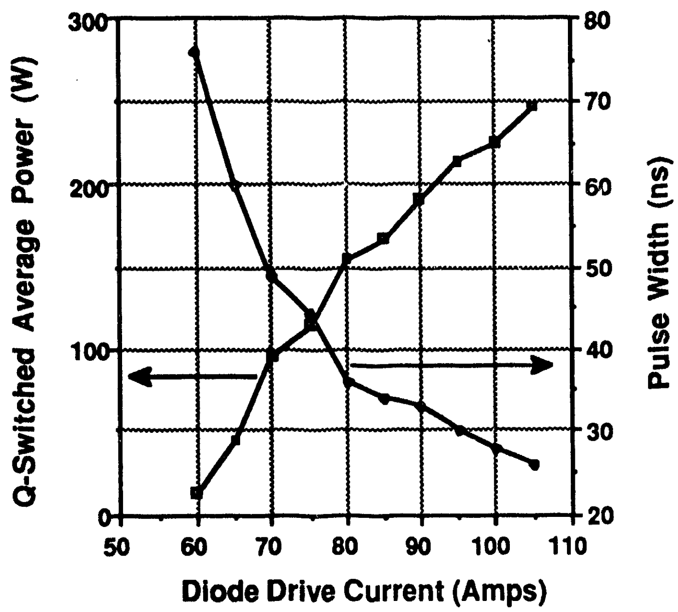

Figure 3. Q-switched average power (squares) and FWHM pulsewidth (filled diamonds) as a function of diode drive current. The pulse repetition rate was 2.5 kHz.

5. FREQUENCY DOUBLING

The frequency conversion experiment is shown schematically in Figure 4. 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.

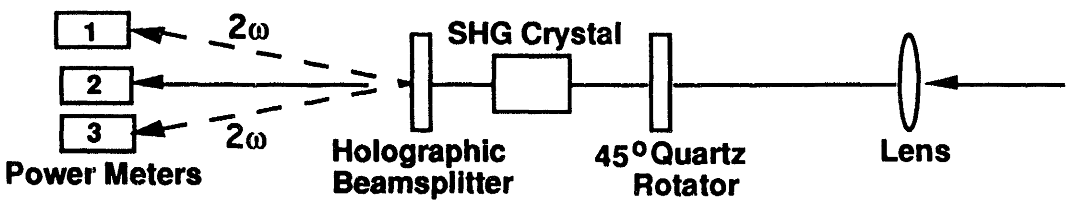

Figure 4. Schematic of the second harmonic generation measurement. Power meters 1 and 3 detect the + and - first order diffracted green power. Power meter 2 detects the undiffracted green and residual red.

The second harmonic power was separated from the residual fundamental by a fused silica holographic beam splitter 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.

Figure 5 shows the measured second harmonic power (the average of the meter readings for the + and - diffraction orders) plotted against the incident average power. At each average power, the phasematching angle was adjusted to maximize the second harmonic signal. Since the pulsewidth decreases and the energy per pulse increases with increasing drive current, we also expect the conversion efficiency to increase, in the absence of thermal dephasing effects[9] caused by the increase in average power. The nearly quadratic dependence of the 0.53 μm power on the 1.06 average power implies that average power induced dephasing effects are not yet causing a rollover in conversion efficiency even at these average powers.

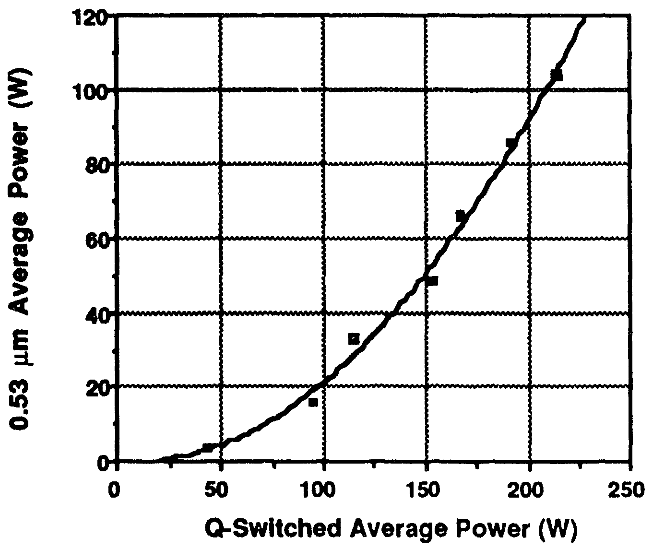

Figure 5. Second harmonic power as a function of the Q-switched average power. The solid line is a least squares fit to a simple quadratic function.

Frequency conversion measurements were made up to a fundamental average power of 200 watts (95 A diode current). At this average power the aperture averaged peak irradiance at 1.06 μm at the doubling crystal was estimated to be 80 MW/cm^2, although 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 catastrophically.

6. 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. 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 focussing our efforts on modifications of the laser which will yield an output beam with a more uniform irradiance profile.

7. ACKNOWLEDGMENT

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