100-W Q-switched Cryogenically Cooled Yb:YAG Laser

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Jeffrey G. Manni, *Member, IEEE*, John D. Hybl, Darren Rand, Daniel J. Ripin, Juan R. Ochoa, and Tso Yee Fan, *Senior Member, IEEE*

***Abstract*—This work describes a cryogenic, electro-optically Q-switched Yb:YAG laser that generates 114-W average TEM_{00} power with 47% optical-to-optical efficiency. Pulse repetition frequency is 5 kHz, pulse duration is 16 ns full-width at half-maximum, and M^2 is less than 1.05.**

***Index Terms*—High-power lasers, solid-state lasers, thermo-optic effects, Yb lasers.**

I. INTRODUCTION

THE advantages of cryogenic cooling (77 K) of Yb:YAG lasers have been confirmed by numerous research groups. This cooling results in four-level laser operation and greatly reduces thermo-optic beam distortion because of the improved thermal conductivity, reduced *dn*/*dT*, and reduced coefficient of thermal expansion of the host crystal [1]. The net result is that high average power and excellent beam quality can be achieved using simple resonator designs, without resorting to phase conjugation or other sophisticated beam cleanup methods [2]–[5].

Another advantage of cryogenic operation of 1030-nm Yb:YAG is that the peak stimulated emission cross section increases by a factor of about 5 as temperature is reduced from room temperature to 77 K. Likewise, the product of emission cross section and upper-state lifetime increases by a similar factor [4], [6]. Saturation fluence and intensity are reduced accordingly, which in turn enables efficient operation of Q-switched oscillators at lower intracavity fluence and efficient amplifier extraction at lower fluence and intensity.

Reported Yb-based 1-μm lasers include continuous-wave (CW) oscillator lasers that generate power levels >450 W [4], [5]; acousto-optically Q-switched lasers that generate 30-mJ, 32-ns pulses at 1.5-kHz pulse repetition frequency (PRF) and as much as 70-W average power at higher pulse rates (5-kHz PRF with 75-ns pulsewidth) [7]; and picosecond regenerative amplifier lasers that generate 8-mJ, 35-ps pulses [8].

Achieving short Q-switched pulses of <20 ns full-width at half-maximum (FWHM) in a high-power, high-gain cryo-Yb laser requires an electro-optic Q-switch (Pockels cell) to maximize extracted pulse energy and minimize Q-switched pulse duration. The opening times for acousto-optic modulator Q-switches are too slow, resulting in significant loss in efficiency for short Q-switched pulses [7]. However, relatively few reports of electro-optically switched cryo-Yb:YAG lasers have been published to date. Kawanaka *et al.* reported an electro-optically Q-switched, cryogenic, ceramic Yb:YAG disk laser that generated 42-mJ, 200-ns pulses at a pulse rate of 10 Hz [9]. The authors indicated that the slope efficiency was low due to poor spatial overlap between the laser mode and gain region. Q-switched pulse duration was long (200 ns) due to a reduced round-trip gain (resulting from poor overlap) and because a 1.75-m-long resonator was used.

This report describes an electro-optically Q-switched, end-pumped, cryogenic Yb:YAG laser that simultaneously achieves more than 100-W average power at 5-kHz PRF, a 16-ns pulse duration, and near-diffraction-limited beam quality. The laser is relatively simple, compact, and robust considering the high level of performance it provides and is expected to achieve high reliability in 24/7-type operations in which the laser could conceivably be used.

II. EXPERIMENTAL

A. Laser Configuration

The electro-optically Q-switched laser configuration is shown in Fig. 1. A 1%-doped Yb:YAG crystal having an undoped endcap is single-end pumped with up to 244 W of 940-nm light from a fiber-coupled laser diode array. The Yb:YAG crystal is a brick 5 mm × 5 mm × 23 mm long that is indium soldered to a copper cold plate in the dewar. The undoped endcap on the pumped end is 1 mm thick so that overall crystal length is 24 mm. The crystal is cooled by pool boiling of the liquid nitrogen in the reservoir above the cold plate. At 100-W output power, approximately 30 W of heat is dissipated by the liquid nitrogen boiloff. This corresponds to a liquid nitrogen consumption rate of approximately 0.01 L/min. Details of the crystal mounting and dewar are similar to those provided in previous publications [2], [7].

Pump light is delivered through a 400-μm, 0.22-NA multimode fiber and is collimated with a 40-mm FL lens. Pump light is then focused into the Yb:YAG crystal through the high-reflector (HR) mirror of the laser resonator using a 150-mm FL spherical lens. The diameter of the gain region in the Yb:YAG crystal is about 1.5 mm.

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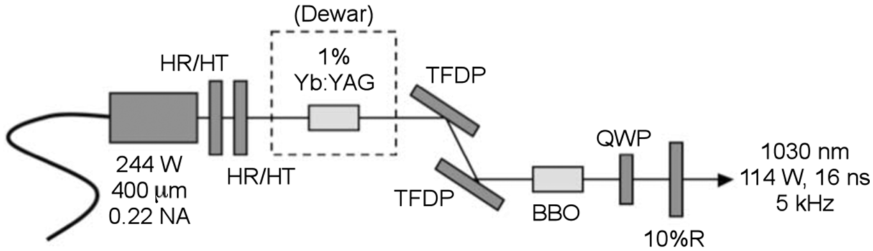

Fig. 1. Layout of electro-optic Q-switched oscillator. HR/HT: highly reflecting (1030 nm)/highly transmitting (940 nm); TFDP: thin-film dielectric polarizer; QWP: quarter-wave plate.

The HR mirror of the laser resonator is highly reflecting ($>99.5\%$) at 1030 nm and highly transmitting ($> 98\%$) at 940-nm pump wavelength. The mirror has a 6-m convex radius of curvature. A second (flat) mirror with the same coating is placed between the HR mirror and the focusing lens so that 1030-nm light leaking through the resonator's HR mirror is not back coupled into the pump laser.

The resonator axis makes a single pass through the Yb:YAG crystal and then bounces off two thin-film dielectric polarizers oriented at 56° angle of incidence. The BBO Pockels cell is a transverse-field, two-crystal device having a 5-mm clear aperture and a quarter-wave voltage of 4.4 kV at 1030 nm. A quarter-wave plate is used to hold off the resonator. High voltage is applied to the Pockels cell to open the laser resonator and generate a Q-switched pulse. The output coupler is a 10% reflecting flat mirror, and overall physical resonator length is 43 cm. Both the output coupler and resonator length were chosen to achieve a pulse duration of 16 ns at 100-W output power.

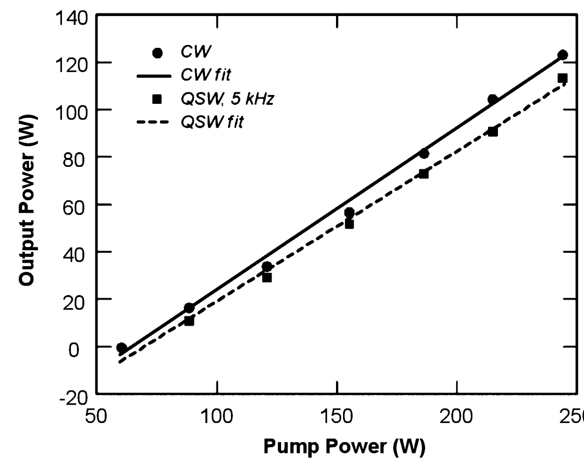

Fig. 2. CW and Q-switched (QSW) input–output data. Slope efficiencies are 68% CW and 63% Q-switched.

B. Measurement Methods

Laser power measurements were made using a water-cooled thermopile power meter. Near-field beam profiles were characterized by performing 1:1 imaging of the beam at the laser's output coupler onto a charge-coupled device-based beam profiler. Beam quality measurements were made by measuring 13.5%-of-peak beam diameters as a function of distance through a waist created with a 25-cm FL lens, and then manually fitting a hyperbola to the data using a simple least-squares method. Far-field pointing stability was measured using the beam profiler to measure beam wander in the focal plane of the 25-cm FL lens over a period of 100 s. Temporal pulse shapes were recorded using an InGaAs photodetector (135-ps rise/fall time) and a 500-MHz bandwidth digital oscilloscope.

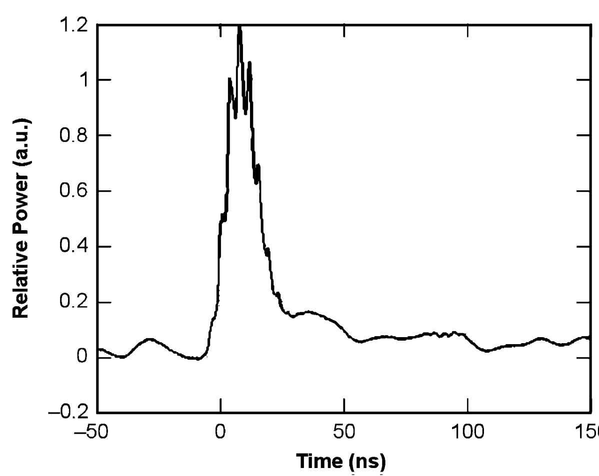

Fig. 3. Q-switched pulse shape (114 W, 5-kHz PRF). The FWHM of the pulse determined by a polynomial fit is 16 ns. The structure in the pulse is due to longitudinal mode beating that is only partially resolved by the scope (500 MHz bandwidth).

III. Results

Input–output data are presented in Fig. 2 for the CW-pumped, electro-optically Q-switched laser operating at 5-kHz PRF. At 244-W maximum pump power, CW power is 123 W and Q-switched average power is 114 W. Laser threshold is approximately 60 W. Average slope efficiency is 68% in CW mode and 63% in Q-switched mode. Absolute efficiency at 244-W pump power is 50% in CW mode and 47% in Q-switched mode.

The Q-switched laser pulse at 114 W average output power is shown in Fig. 3. The measured pulsewidth is 16 ns FWHM. The temporal profile was recorded using the full bandwidth of the oscilloscope and represents an average of 16 pulses.

Shown in Fig. 4(A) is the near-field beam profile at 114 W output power and 5-kHz PRF. The profile is a 1:1 image of the beam at the laser's output coupler; at 114 W the beam diameter $(1/e^2)$ is 1.2 mm. This value decreases as output power increases, reflecting changes in thermal lensing and gain guiding;

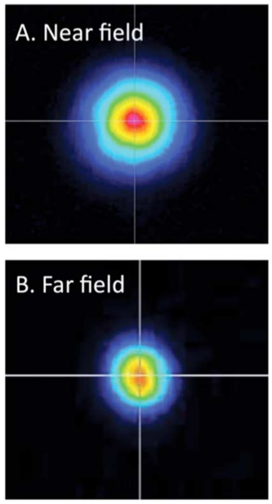

Fig. 4. (A) 1:1 image of the beam at the output coupler (Q-switched, 114 W). Beam diameter is 1.2 mm $(1/e^2)$. (B) Far-field beam profile at focus of 25-cm FL lens. Beam diameter $(1/e^2)$ at focus is 260 μm at 114-W output power.

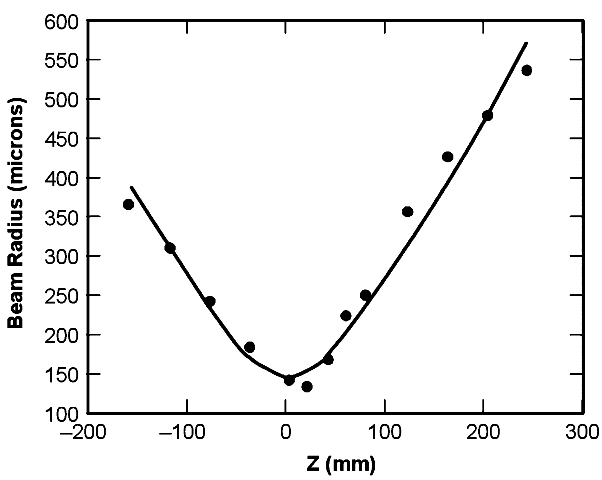

Fig. 5. M^2-fit data (Q-switched, 114 W). The calculated curve is for $M^2 = 1.00$.

beam diameter is 1.8 mm at 30 W, 1.6 mm at 57 W, and 1.4 mm at 90 W.

The far-field beam profile at the focus of a 25-cm FL lens is shown in Fig. 4(B). Far-field beam diameter at 114 W is 260 μm. Far-field spot diameter and beam divergence increase as pump power and output power increase, which is consistent with near-field beam diameter becoming smaller as output power increases.

Beam quality is $M^2 < 1.05$ in both directions at 114 W and all lower power levels. Fig. 5 shows a typical fit of beam diameter data to a calculated hyperbola with $M^2 = 1.00$. The beam was nearly round at all z positions; data were virtually identical in the x and y transverse dimensions.

As seen in Fig. 5, hyperbolic fits were quite good when determining M^2 values. This is because little or no diffracted energy exists around the main beam, which is a direct result of the soft-aperture gain medium created by the end-pumping configuration. Fits are also very good due to minimal presence of non-parabolic index gradients that can diffract mode energy when mode diameter is about the same size as, or larger than, pump beam diameter [10], [11].

Far-field pointing stability was measured at 1-s intervals over a period of 100 s and at 114-W output power. Pointing stability was ± 21 μrad (mean deviation), ± 24 μrad (rms deviation), and ± 60 μrad (maximum deviation). These numbers were measured after letting the laser stabilize for about 5 min at the set point power level. (Full-angle beam divergence at $1/e^2$ intensity points is 1.1 mrad.) Little or no effort was made to eliminate air currents in the resonator. Values were about a factor of two larger when measured from a cold start.

IV. Summary

The advantageous spectroscopic and thermo-optic properties of cryogenic-Yb:YAG make it an ideal gain material for efficient high-power CW or pulsed oscillators and amplifiers. The laser demonstrated in this paper provides an efficient, high-brightness, well-controlled pulsed laser source.

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