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Citation	Manni, J.G. et al. "100-W Q-switched Cryogenically Cooled Yb:YAG Laser." <i>Quantum Electronics, IEEE Journal of</i> 46.1 (2010): 95-98. © 2009 Institute of Electrical and Electronics Engineers.
As Published	http://dx.doi.org/10.1109/jqe.2009.2027717
Publisher	Institute of Electrical and Electronics Engineers
Version	Final published version
Accessed	Tue Aug 21 15:47:49 EDT 2018
Citable Link	http://hdl.handle.net/1721.1/55360
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100-W Q -switched Cryogenically Cooled Yb:YAG Laser

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 TEM₀₀ 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].

Manuscript received March 19, 2009; revised June 09, 2009. Current version published December 04, 2009. This work was supported by the Missile Defense Agency under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are not necessarily endorsed by the United States Government.

J. G. Manni is with JGM Associates Inc., Burlington, MA 01803 USA (e-mail: jgmanni@jgma-inc.com).

J. D. Hybl, D. Rand, D. J. Ripin, J. R. Ochoa, and T. Y. Fan are with the Massachusetts Institute of Technology (MIT) Lincoln Laboratory, Lexington, MA 02420 USA (e-mail: jhybl@ll.mit.edu; drand@ll.mit.edu; dripin@ll.mit.edu; jochoa@ll.mit.edu; fan@ll.mit.edu).

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Digital Object Identifier 10.1109/JQE.2009.2027717

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 \times 5 mm \times 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 multi-mode 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.

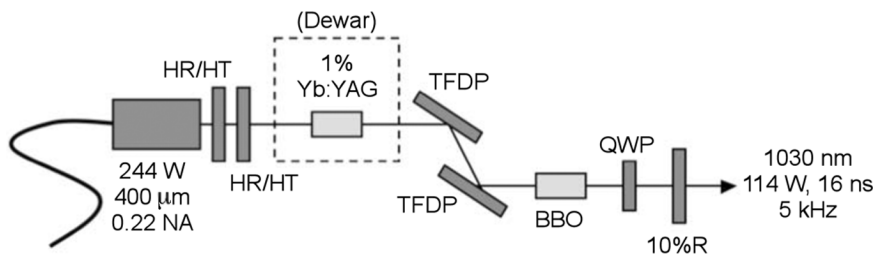


Fig. 1. Layout of electro-optic Q -switched oscillator. HR/HT: highly reflecting (1030 nm)/highly transmitting (940 nm); TFDP: thin-film dielectric polarizer; QWP: quarter-wave plate.

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.

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.

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.

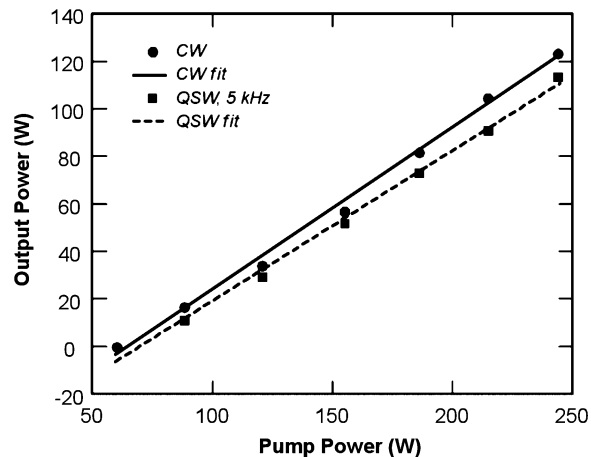


Fig. 2. CW and Q -switched (QSW) input-output data. Slope efficiencies are 68% CW and 63% Q -switched.

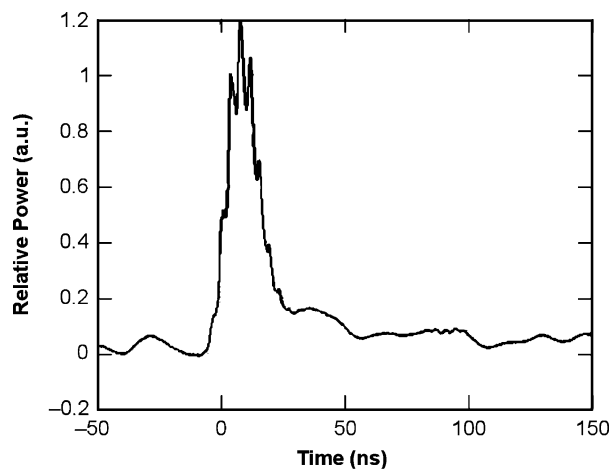


Fig. 3. Q -switched pulse shape (114 W, 5-kHz PRF). The FWHM of the pulse determined by a polynomial fit is 16 ns. The structure in the pulse is due to longitudinal mode beating that is only partially resolved by the scope (500 MHz bandwidth).

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;

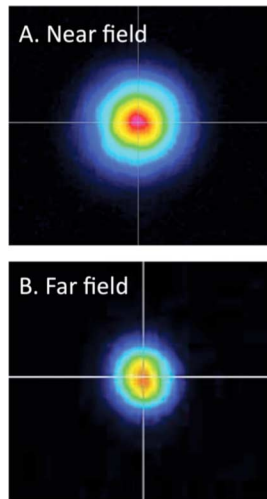


Fig. 4. (A) 1:1 image of the beam at the output coupler (Q-switched, 114 W). Beam diameter is 1.2 mm ($1/e^2$). (B) Far-field beam profile at focus of 25-cm FL lens. Beam diameter ($1/e^2$) at focus is 260 μm at 114-W output power.

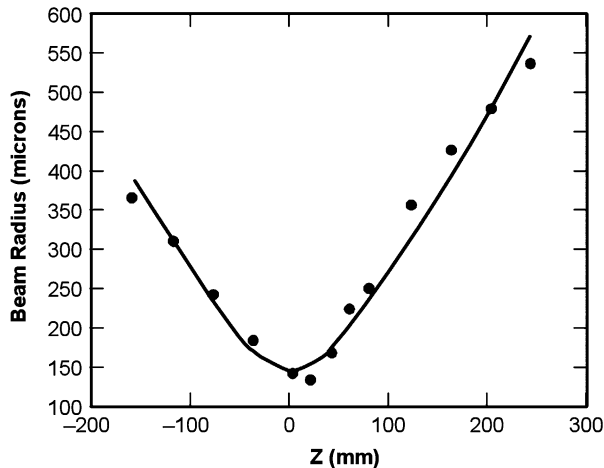


Fig. 5. M^2 -fit data (Q-switched, 114 W). The calculated curve is for $M^2 = 1.00$.

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 $\pm 21 \mu\text{rad}$ (mean deviation), $\pm 24 \mu\text{rad}$ (rms deviation), and $\pm 60 \mu\text{rad}$ (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.

ACKNOWLEDGMENT

The authors thank J. Daneu and P. Hassett for fabrication of laser crystals and P. Foti for general laboratory assistance.

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Jeffrey G. Manni (M'88) was born in Russellton, PA, on June 2, 1955. He received the B.S. degrees in chemistry and physics from the Massachusetts Institute of Technology, Cambridge, MA, in 1977 and 1978, respectively, the M.S. degree in applied physics from Stanford University, Stanford, CA, in 1980, and the M.B.A. degree (high technology management program) from Northeastern University, Boston, MA, in 1987.

From 1980 to 1988, he worked as a laser scientist/engineer at Quanta Ray, Candela Corporation, Raytheon Laser Products, and Schwartz Electro-Optics. He has been working as an independent laser, electro-optics, and nonlinear optics engineer since 1988 as President of JGM Associates, Inc. in Burlington, MA. He contributes to research activities at MIT Lincoln Laboratory as a sub-contractor. His research interests include diode-pumped solid-state lasers, optical parametric oscillators and amplifiers, and applications of lasers in biomedical and biotechnology instrumentation.

Mr. Manni is a member of the Optical Society of America and SPIE.

John D. Hybl received a B.S. degree in chemistry from Michigan State University in 1996 and a Ph.D. in physical chemistry from the University of Colorado at Boulder in 2001.

He has been a member of the technical staff at MIT Lincoln Laboratory since 2002. At Lincoln he has worked on developing optical methods for the rapid detection of biological and chemical agents. Recently, he has been working to develop cryogenic Yb:YAG for high-power laser applications.

Darren Rand received a B.E. degree in electrical engineering from The Cooper Union in 2001 and a Ph.D. degree from Princeton University in 2006, where he worked on nonlinear and quantum optics, as well as fiber optic communication systems.

Since 2006, he has been a member of the technical staff at MIT Lincoln Laboratory. He has worked on the thermal characterization of laser crystals and development of high-power cryogenic Yb:YAG laser technology.

Daniel J. Ripin received a B.S. degree in physics from Emory University, Atlanta, GA, in 1995 and a Ph.D. degree in physics from the Massachusetts Institute of Technology, Cambridge, MA, in 2002. His dissertation research focused in the areas of ultrafast optics, photonic crystals, and integrated optics.

He is the Assistant Leader of the Laser Technology and Applications Group at MIT Lincoln Laboratory. Since 2002, at MIT Lincoln Laboratory, his research has been in the areas of high-average-power laser development, ultrafast optics, and spectroscopy.

Dr. Ripin is a member of the Optical Society of America (OSA).

Juan R. Ochoa received a S.B. degree in physics from the University of Washington, Seattle, WA, in 1976, on full scholarship from the USAF.

He is an Assistant Staff Member in the Laser Technology and Applications Group of the Solid State Division at M.I.T. Lincoln Laboratory with over 30 years of experience in semiconductor and other solid state lasers. He was born in Seattle, WA on June 27, 1954. In 1976 he joined Exxon Nuclear Laser Isotope Separation program working with high-powered dye lasers. After fulfilling his obligations to the Air Force in 1978, he began work at Tektronix, Beaverton, OR, developing laser trimming processes for integrated and hybrid circuits. In 1984, he joined Control Laser of Orlando, FL as part of the re-design team for their primary Nd:YAG laser system. In 1985, he moved to Teradyne in Boston, MA where he was Laser Engineer for their laser trimming product line. Since 1988 he has been an Assistant Staff member at M.I.T. Lincoln Laboratory, Lexington, MA in the Laser Technology and Applications Group. The focus of his work at Lincoln Laboratory has been solid-state lasers including microchip lasers, external-cavity diode lasers, mid-infrared lasers, and for the last few years, high-powered cryogenically cooled Yb:YAG lasers.

Tso Yee Fan (S'82–M'87–SM'96) received the S.B. degrees in electrical engineering and materials science and engineering from the Massachusetts Institute of Technology (MIT), Cambridge, MA, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA.

He is an Associate Leader of the Laser Technology and Applications Group at MIT Lincoln Laboratory, Lexington, MA. He joined MIT Lincoln Laboratory as a Staff Member in 1987. He has contributed broadly in solid-state laser and nonlinear optics technology. He is widely recognized for his work in diode-pumped solid-state lasers, in the development of Yb:YAG lasers, in characterization of laser and nonlinear optical materials, and for advances in laser beam combining.

Dr. Fan is a Fellow of the Optical Society of America (OSA). He served as an Elected Member of the IEEE/LEOS Board of Governors from 1994–1996 and was the Topical Editor, Lasers for Optics Letters from 1994–1999. He served as Division Editor for the Lasers, Photonics, and Environmental Optics Division of Applied Optics from 2005–2007. He has served on program committees of numerous conferences, including as Chair of the LEOS Annual Meeting and Chair of the OSA Topical Meeting on Advanced Solid-State Lasers.