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

The MIT Faculty has made this article openly available. *Please share* how this access benefits you. Your story matters.

| Citation      | Manni, J.G. et al. “100-W Q-switched Cryogenically Cooled Yb:YAG Laser.” Quantum Electronics, IEEE Journal of 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      | Fri Dec 07 16:41:37 EST 2018                                                                                                                                                                     |
| Citable Link  | http://hdl.handle.net/1721.1/55360                                                                                                                                                              |
| Terms of Use  | Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.                                       |
| Detailed Terms|                                                                                                                                                                                                 |
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 and upper-state lifetime 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 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 $\times$ 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 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.
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. 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;
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.

REFERENCES

[1] R. L. Aggarwal, D. J. Ripin, J. R. Ochoa, and T. Y. Fan, “Measurement of thermo-optic properties of Y$_3$Al$_5$O$_{12}$, Lu$_3$Al$_5$O$_{12}$, YAlO$_3$, LiYF$_4$, LiLuF$_4$, BaY$_2$F$_6$, KGd(WO$_4$)$_2$, KY(WO$_4$)$_2$, and KGd(WO$_4$)$_2$ laser crystals in the 80–300 K temperature range,” J. Appl. Phys., vol. 98, no. 10, pp. 103514–1–103514-14, 2005.

[2] D. J. Ripin, J. R. Ochoa, R. L. Aggarwal, and T. Y. Fan, “300-W cryogenically cooled Yb:YAG laser,” IEEE J. Quantum Electron., vol. 41, no. 10, pp. 1274–1277, Oct. 2005.

[3] D. J. Ripin, J. R. Ochoa, R. L. Aggarwal, and T. Y. Fan, “165-W cryogenically cooled Yb:YAG laser,” Opt. Lett., vol. 29, no. 18, pp. 2154–2156, 2004.

[4] T. Y. Fan, D. J. Ripin, R. L. Aggarwal, J. R. Ochoa, B. Chann, M. Tilleman, and J. Spitzberg, “Cryogenic Yb$^{3+}$-doped solid-state lasers,” IEEE J. Sel. Top. Quantum Electron., vol. 13, no. 3, pp. 448–459, May/June 2007.

[5] D. C. Brown, J. M. Singley, E. Yager, K. Kowaleski, I. Guzelzow, and J. W. Kuper, “Kilowatt class high-power cw Yb:YAG cryogenic laser,” SPIE Proc., vol. 6952, 2008, paper 69520K.

[6] J. Dong, M. Bass, Y. Mao, P. Deng, and F. Gan, “Dependence of the Yb$^{3+}$ emission cross section and lifetime on temperature and concentration in yttrium aluminum garnet,” J. Opt. Soc. Am. B, vol. 20, no. 9, pp. 1975–1979, 2003.

[7] S. Tokita, J. Kawanaka, M. Fujita, T. Kawashima, and Y. Izawa, “Efficient high-average-power operation of Q-switched cryogenic Yb:YAG laser oscillator,” Jpn. J. Appl. Phys., vol. 44, no. 50–52, pp. L1529–L1531, 2005.

[8] Y. Akahane, M. Aoyama, K. Ogawa, K. Tsuji, S. Tokita, J. Kawanaka, H. Nishioka, and K. Yamakawa, “High-energy, diode-pumped, picosecond Yb:YAG chirped-pulse regenerative amplifier for pumping optical parametric chirped-pulse amplification,” Opt. Lett., vol. 32, no. 13, pp. 1899–1901, 2007.

[9] J. Kawanaka, S. Tokita, N. Nishioka, K. Ueda, M. Fujita, T. Kawashima, H. Yagi, and T. Yanagisawa, “42 mJ Q-switched active-mirror laser oscillator with a cryogenic Yb:YAG ceramic,” OSA Adv. Solid State Photon., 2007, paper MB2.pdf.

[10] J. Frauchiger, P. Albers, and H. P. Weber, “Modeling of thermal lensing and higher order ring mode oscillation in end-pumped C-W Nd:YAG lasers,” IEEE J. Quantum Electron., vol. 28, no. 4, pp. 1046–1056, Apr. 1992.

[11] Y. F. Chen, Y. P. Lan, and S. C. Wang, “Efficient high-power diode-end-pumped TEM$_{00}$ Nd:YVO$_4$ laser with a planar cavity,” Opt. Lett., vol. 25, no. 14, pp. 1016–1018, 2000.
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 subcontractor. 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.