Cryogenic Yb:YAG composite-thin-disk for high energy and average power amplifiers

Luis E. Zapata,1,3∗ Hua Lin,2 Anne-Laure Calendron,1,2 Huseyn Cankaya,1,2 Michael Hemmer,1 Fabian Reichert,1 W. Ronny Huang,1 Eduardo Granados,3,4 Kyung-Han Hong,1 and Franz X. Kärtner,1,2,3

1Center for Free-Electron Laser Science, Deutsches Elektronen-Synchrotron, Notkestrasse 85, 22607 Hamburg, Germany
2Department of Physics and The Hamburg Centre for Ultrafast Imaging, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
3Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts 02139, USA.
4IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

*Corresponding author: luis.zapata@celf.de

Received Month X, XXXX; revised Month X, XXXX; accepted Month X, XXXX; posted Month X, XXXX (Doc. ID XXXXX); published Month X, XXXX

A cryogenic composite-thin-disk amplifier with amplified spontaneous emission (ASE) rejection is implemented that overcomes traditional laser system problems in high-energy pulsed laser drivers of high average power. A small signal gain of 8 dB was demonstrated compared to 1.5 dB for an uncapped thin-disk without ASE mitigation under identical pumping conditions. A strict image-relayed 12-pass architecture using an off-axis vacuum telescope and polarization switching extracted 100 mJ at 250 Hz in high beam quality stretched 700 ps pulses of 0.6-mm bandwidth.

OCIS codes: (140.3280) Laser amplifiers; (140.3538) Lasers pulsed; (140.3480) Lasers, diode-pumped

High gain and uniform heat removal in a Nd:glass zigzag slab geometry for mitigation of thermo-optical effects with phase conjugation inside a strictly relayed multipass optical architecture have been central to the significant high mark in performance of the high energy pulsed (>25 J, 14 ns), high average power (150 W) solid-state laser of diffraction-limited output in [1]. We are exploring simpler alternatives for scaling laser amplifiers utilizing thin-disk geometries, cryogenic cooling techniques and the better intrinsic material and spectroscopic properties found in modern Yb3+-doped crystals for the generation of energetic ultrashort pulses at high repetition rates. The small quantum defect minimizes heat load while the availability of high-brightness diodes allows for pumping with high intensities. For average power scaling, the thin-disk geometry is a proven technique for enhanced cooling [2] as well as mitigation of thermo-optical effects. Room-temperature Yb:YAG and Yb:LuAG have emerged as the most successful and frequently used high-power laser materials in this geometry [3]. Output power in excess of 8.5 kW from a single thin-disk in continuous wave operation has been reported albeit with reduced beam quality [4]. Also in reference [4], researchers at Trumpf Laser GmbH summarily report achieving a beam quality of M2~1.4 in the laboratory at 4-kW output from a single disk.

Advances in high average power with high beam quality have also come from operating Yb3+-doped materials at liquid nitrogen temperature extending by nearly 100-fold the useful output of rod-type amplifiers and demonstrating high-gain and low spatial distortion with excellent performance in the amplification of short pulses [5,6,7].

Here we combine the intrinsic advantages of the thin-disk geometry with the thermo-mechanical and thermo-optical leverage afforded by liquid nitrogen cooling Yb3+:YAG crystals to enable high energy pulses at high average power and diffraction limited performance simultaneously. To achieve high pulse energy, which requires high gain, we are using a variant of the thin-disk: the composite-thin-disk (CTD) pioneered at LLNL [8, 9] that mitigates ASE, extending gain-storage performance and aperture scaling. The cryogenic CTD prototypes in these experiments had a 4.5-mm aperture comprising a 1-mm thick 10%Yb:YAG disk optically bonded to a 4-mm thick undoped YAG-crystal “cap” with shaped edges fashioned to eject fluorescence. In this Letter we report on gain-storage measurements with this CTD prototype compared with an uncapped disk under identical conditions. We also report on the extraction of 100 mJ chirped pulses at 250 Hz from a single CTD using a compact 12-pass strictly relayed optical architecture. Our interest is scaling optical parametric chirped pulse amplifiers (OPCPAs) for applications requiring energetic pulses and high repetition rates such as high-flux high-harmonic generation [10]. Further scaling will use the 100-mJ class chirped pulse amplifier reported in this Letter as the first stage to larger Joule class systems.

At the heart of our laser driver is a diode pumped cryogenic CTD amplifier assembly depicted in Fig. 1. On the cooled face, the laser-grade high-reflector exists in thermal contact –through soldering– with liquid nitrogen cooled, heat-spreader. The opposite face of the disk shaped gain-volume is bonded to the index-matched “cap” of undoped YAG. The function of the cap is to dilute fluorescence diminishing the deleterious influence of ASE. The parabolic sidewalls have a smooth specular polish and efficiently eject
fluorescence avoiding recirculation. The addition of a 
fully transparent cap does not affect the 
predominantly 1D thermal distribution in the gain 
volume, which in our finite-element thermal models 
was nearly identical in the CTD and uncapped disk. 
The undoped thermally insulated cap does not 
develop gradients rising to a uniform temperature, a 
benign effect that does not affect wavefront. The 
added thickness however results in a much stiffer 
gain element that is resilient to deformations [11].

The designs had comparable energetics and thermal 
performance, we tested a CTD and an uncapped disk 
in free running mode. A stable linear resonator was 
configured 1 m long arranged with a 30 cm lens at the 
midpoint and a flat 90% reflectivity output 
coupler. In tests, 495-W diode pulses 1 ms in 
duration pumped the gain elements at up to 300 Hz. 
The uncapped disk and the CTD produced multi-
mode beams that filled the aperture with comparable 
output averaging 68 and 72 Watts, respectively. We 
concluded from these data that under saturated (low) 
gain conditions, the CTD and uncapped disk perform 
equivalently.

The small signal or “storage” gain was measured 
directly after six passes (with the multipass 
arrangement described later in this Letter) using the 
expanded 4 mm-diameter, Gaussian-shaped 200-ps 
seed pulses from an Yb:KYW regenerative amplifier 
(Amplitude Systemes S-Pulse™). To avoid saturating 
the gain, the beam was attenuated to ~50 µJ/pulse 
and pulse picked timing the arrival of the probe 
pulses at the end of “square” diode-pump pulses 1 ms 
in duration. The repetition rate of 20-Hz was selected 
to avoid thermal effects. The small signal gain per 
bounce (or double-pass) was obtained as $\ln(G_p) = \frac{\ln(E_p/E_{in})}{2}$ 
where $E_p$ is the pulse energy after six gain 
passes and, $E_{in}$ the transmitted pulse energy 
measured identically under un-pumped conditions. 
The characteristic storage gain for the CTD and 
uncapped disk were dramatically different as can be 
seen in Fig. 2, which plots the double pass gain vs. 
stored energy per unit area using (1). The storage 
gain can be expressed as,

$$\ln(G_p) = \Delta N \sigma L = \frac{(1-QD)}{hv/\sigma} \frac{P_{abs} \tau}{\pi \sigma^2} \left(1 - e^{-t_p/\tau}\right)$$ (1).

Here, the left hand corresponds to the experimental 
small signal gain followed by its (4-level) definition 
where $\Delta N$ is the inversion density at the end of the 
pump pulse, $\sigma$ the emission cross section and $L$ the 
gain-length along the probe dimension. In the right 
hand $\Delta N$ has been expanded to account for decay 
during the pump pulse and simplified to an 
expression based on the known or measurable 
quantities, where $QD=0.1\%$ is the quantum defect, 
$P_{abs}$ is the measured absorbed power, $\tau=960 \mu$s is the 
upper level lifetime, $t_p = 1 ms$ is the diode-pump 
pulse duration, $hv$ is the laser-photon energy and $\pi \sigma^2$ 
the pumped area of radius $r = 2.2 \, mm$. In the absence 
of saturating effects the right hand in (1) is the 
energy stored in the upper laser level (ULL) per unit 
area divided by the saturation fluence $E_{sat} = hv/\sigma$, 
linearly dependent on the applied pump power with 
slope equal to $1/E_{sat}$.

As can be seen in figure 2, the double-pass gain 
rolls over reaching a limit of 8 dB at the highest

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**Fig. 1.** A composite thin-disk (CTD) gain-element assembly 
is shown in this 3D model. The CTD 4.5 mm clear aperture 
comprises a 1 mm thick 10% Yb:YAG gain volume (red) 
bonded to a 4 mm thick undoped YAG “cap” (blue). The 
parabolic sides were designed with the aid of a Monte-
Carlo ray trace code to maximally eject fluorescence. The 
CTD is contacted thermally to the expansion-matched heat 
spreaders (in yellow) via soldering. The backplane 
interfaces to the cold finger of a liquid nitrogen Dewar.

CTD and uncapped gain elements were soldered to 
respective heat spreaders then contacted with a 
compressed indium gasket to the cooling plate of a 
commercial Dewar to complete assembly. Boiling 
liquid nitrogen in the Dewar supplied primary 
cooling from the top and an anti-reflection (AR)- 
coated vacuum window provided optical access to the 
gain element from below. A 500-W fiber-coupled 
diode laser (Laserline GmbH) at 940 nm was initially 
used as the pump source. A customized optical 
package projected a 4.4 mm diameter smooth, 
early-flattop pump profile (< 10% roll) at a distance of 
180 mm. This image was cast onto the CTD 
through the AR coated front face at 13° angle of incidence filling most of the 4.5 mm diameter high-
reflection (HR) coated backplane. The diode pump 
bounced off the CTD backplane making a second 
pass through the gain volume and the unabsorbed 
pump was collected by a thermopile. The diodes were 
temperature tuned and the absorption optimized at 
90% in this simple double-pass arrangement. 
Uncapped disks of dimensions and doping identical 
to the CTD’s gain-volume were fabricated and tested 
to provide performance baselines. To ascertain that
pump power (the system was later upgraded with the installation of an analogous but more powerful 2-kW diode pump unit from Laserline GmbH to extend the small signal gain performance). We attribute this evolution to the saturating effect of transverse ASE [11]. The initial slope in figure 2 yields the effective pulse saturation fluence $E_{sat}=3.5\,\text{J/cm}^2$.

Two identical 3"-diameter, $f=300$ mm plano-convex lenses doubling as vacuum windows were separated by an afocal distance $(2:f)$ set with the aid of a shear-plate during assembly. A formatted Gaussian P-polarized seed entered through a thin-film polarizer (TFP) filling the 4-mm input/output aperture (in the lower right corner of Figs. 3 and 4). The seed entered the first lens off-center and parallel to the optical axis (OA) at the position of 5 o’clock (red trace in Fig. 3). At the other end of the telescope, a 45° prism and six-mirror kaleidoscope (angled by 5°) deflected the seed towards the CTD reaching the HR at precisely the imaging distance of 4·f from the input/output aperture (a crosshair at the input aperture was imaged onto the CTD during alignment). The beam “bounced” off the CTD HR returning the amplified beam after two gain passes on a symmetric path. The beam exited diametrically opposed at the input lens (at 11 o’clock) and was deflected with two adjustable mirrors towards another off-axis entry point in the first lens (at 3 o’clock) repeating this pattern twice more (green trace and blue trace in Fig. 3) exiting at the position of 7 o’clock. Having passed the gain medium 6 times, the quarter wave plate and back mirror rotated the polarization from P to S returning the amplified beam for another 6 gain passes thus: the near field was strictly relayed in 12 gain passes through the CTD saturating the gain while becoming super-Gaussian. A 2-mm aperture in the vacuum telescope attenuated spatial features smaller than 0.3 mm insuring a smooth beam throughout for low damage risk. The round-trip transmission (per “bounce” or, two gain passes) measured 92%.

Fig. 2. The double-pass small-signal gain for an uncapped disk (*) and a composite thin disk (**) were measured using a 500-W diode pump at low duty factor. A 2-kW pump was later installed extending the CTD performance to the ASE limit (*). The inset shows a CTD/heat-spread assembly.

This value is approximately twice the published value for narrow band operation at 100 K [5] and consistent with the 0.5 nm output linewidth (measured with an ANDO spectrometer) averaged over the 1-nm gain bandwidth at this temperature.

To extract high pulse energy efficiently, we devised a strictly relayed 12-pass architecture utilizing a 1:1 vacuum telescope off-axis. The optical components and beam passage is depicted in Fig. 3. The 12-pass hardware and elevated cryogenic Dewar containing the CTD can be seen in the picture, Fig. 4.

Chirped pulse extraction yielded results presented in Figs. 5 and 6. In these experiments, the diode

Fig. 3. Ray-trace of the strictly relayed 12-pass optical architecture used. The telescope is truncated in this diagram and the input/output TFP omitted for clarity. The inset on the upper right depicts the beam footprint: image and polarization rotation (R and white arrow respectively).

Fig. 4. The 12-pass hardware is shown in this picture. The CTD is mounted inside the liquid nitrogen Dewar and accessed from below. Precision-machined surfaces keyed the alignment of the optics.
pump delivered square pulses of 250-µs duration at up to 2-kW, deemed as the best compromise between heat deposition and gain. Seeded with the 1.8-mJ, chirped 2.2-ns pulse from a homebuilt Yb:KYW system described elsewhere [12], the CTD produced up to 110 mJ at 100 Hz with 35% slope and 26% overall optical efficiency. At higher repetition rates the slope decreased producing 100 mJ at 250 Hz with 22% slope, 21% overall optical efficiency. The far-field at the focus of a f=300-mm lens was round with 1/e² diameter that remained less than 1.1-times diffusion-limited when compared to the 2.44 λ/D ideal central lobe expected if the near field (D=3.3-mm) in Fig. 5 were uniformly illuminated. The far-field diagnostic showed the rapid onset of blooming as the average output power increased beyond 35 W, the maximum reported in Fig. 5. The pointing and energy stability was measured at mid-power, averaging ±20-µRad and ±2.5% respectively over a 90-minute span.

The spectral overlap between the seed and gain profile was estimated at ~0.66 mJ resulting in an in-band signal gain greater than 100 at maximum pump. Measured spectra for the seed and, for the output at 20 Hz and 250 Hz are shown in Fig. 6. At 20 Hz, the bandwidth at maximum gain was 0.47 nm however: at 250 Hz, the bandwidth increased to 0.61 nm presumably due to the higher operating temperature within the gain medium. The output pulse width at maximum gain was 700 ps. The depolarization was rejected at the input Faraday isolator never exceeding 1.5% of the output power.

In conclusion, high gain was demonstrated with a newly designed Yb:YAG/YAG composite thin-disk operated cryogenically. A strictly relayed 12-pass optical architecture was used to extract 100 mJ chirped pulses at 250 Hz demonstrating the benefits afforded by the combination of these techniques for high energy and high average power. We are planning on larger CTDs and aggressive cooling technologies for higher performance (1-J at 1-kHz).

![Fig. 6. The measured seed spectrum and, gain-narrowed output spectra at 100 mJ output for 20 Hz and 250 Hz are compared. The vertical scale is in arbitrary units.](image)

We appreciate the many helpful discussions with T. Y. Fan, Darren Rand, Leo Missaggia and Michael Brattain of MIT-Lincoln Laboratory and their professional assistance with indium bonding technology. We further thank Andrew Ryan and Andrew Gallant of the MIT machine shop, Lars Gumprecht of DESY and their engineering support teams. This work was supported through the DESY-MIT Collaboration and “The Hamburg Centre for Ultrafast Imaging: Structure, Dynamics and Control of Matter at the Atomic Scale” of the Deutsche Forschungsgemeinschaft.

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