All-diode-pumped quasi-continuous burst-mode laser for extended high-speed planar imaging

Mikhail N. Slipchenko
Spectral Energies

Joseph D. Miller
Spectral Energies

Sukesh Roy
Spectral Energies

James R. Gord
Air Force Research Laboratory

Terrence R. Meyer
Iowa State University, trm@iastate.edu

Follow this and additional works at: http://lib.dr.iastate.edu/me_pubs

Part of the Mechanical Engineering Commons

The complete bibliographic information for this item can be found at http://lib.dr.iastate.edu/me_pubs/168. For information on how to cite this item, please visit http://lib.dr.iastate.edu/howtocite.html.
All-diode-pumped quasi-continuous burst-mode laser for extended high-speed planar imaging

Mikhail N. Slipchenko, 1 Joseph D. Miller, 1, 2 Sukesh Roy, 1 James R. Gord, 3 and Terrence R. Meyer 2,*

1 Spectral Energies, LLC, Dayton, OH 45431, USA
2 Department of Mechanical Engineering, Iowa State University, Ames, IA 50011, USA
3 Air Force Research Laboratory, Propulsion Directorate, Wright-Patterson AFB, OH 45433, USA

tmm@iastate.edu

Abstract: An all-diode-pumped, multistage Nd:YAG amplifier is investigated as a means of extending the duration of high-power, burst-mode laser pulse sequences to an unprecedented 30 ms or more. The laser generates 120 mJ per pulse at 1064.3 nm with a repetition rate of 10 kHz, which is sufficient for a wide range of planar laser diagnostics based on fluorescence, Raman scattering, and Rayleigh scattering, among others. The utility of the technique is evaluated for image sequences of formaldehyde fluorescence in a lifted methane–air diffusion flame. The advantages and limitations of diode pumping are discussed, along with long-pulse diode-bar performance characteristics to guide future designs.

©2013 Optical Society of America

OCIS codes: (120.1740) Combustion diagnostics; (140.3538) Lasers, pulsed; (140.3280) Laser amplifiers; (300.2530) Fluorescence, laser-induced.

References and links


1. Introduction

The study of chemical species and thermodynamic quantities (e.g., temperature, heat release, etc.) in reacting flows is critical for understanding the performance and emissions of power-generation and propulsion systems. Recently, several research groups have employed high-repetition-rate planar laser-induced fluorescence (PLIF) to investigate combustion intermediates in turbulent reacting flows using continuously pulsed diode-pumped solid state (DPSS) laser technology [1-7]. Laser system requirements include tunable ultraviolet (UV) output, narrow spectral bandwidth for efficient frequency conversion and excitation of combustion intermediates, high repetition rate for investigation of transient phenomena, short pulse width for discrimination against background interferences, and high pulse energies for planar measurements. High pulse energy limits the use of continuously pulsed, multi-kHz-rate DPSS lasers because of the difficulty in achieving very high average optical power (kW range) while satisfying other system requirements. Hence, the per-pulse energies of current DPSS-based high-speed imaging systems are insufficient to pump solid-state optical parametric oscillators (OPO’s) and require dye lasers, which are limited by saturation and degradation of the laser dye, for frequency conversion. Furthermore, multi-photon absorption within conventional solid-state crystals can limit the average power and, correspondingly, the UV conversion efficiency. The low pulse energy ultimately restricts the number of flow parameters that can be measured and inhibits the use of diagnostic techniques such as Raman scattering, Rayleigh scattering, laser-induced incandescence, and PLIF of some key fuel tracers and combustion species. Hence, only a few combustion species have been investigated, and the maximum repetition rate is typically ~10 kHz because of the limited laser energy of current laser hardware [1-7].

To overcome the challenges associated with conventional high-average-power continuously pulsed DPSS lasers, it is possible to employ burst-mode laser technology in
which the pulse sequence can reach energies of 100’s of mJ per individual pulse up to MHz rates, while maintaining low average power [8–12]. This technology has been demonstrated for high-speed measurements of temperature [13]; mixture fraction [14]; PLIF of OH [10, 15], NO [12, 16, 17], CH [18–20], and CH$_2$O [21, 22]; and Raman line imaging of O$_2$, N$_2$, CH$_4$, and H$_2$ [23], with measurements ranging from 1 kHz to 1 MHz. One approach to burst-mode operation is to utilize multiple oscillator–amplifier chains in a parallel configuration, allowing up to eight high-energy pulses in a time-correlated sequence [15]. To increase the number of pulses, it is also possible to amplify a sequence of low-energy pulses from a chopped continuous-wave (cw) master oscillator through a series of flashlamp-pumped amplifiers [8].

The duration of a discharge through the flashlamps determines the duration of the burst and has been previously limited to ~1 ms. However, many reacting flows of practical interest have characteristic oscillation periods of 10’s of μs to 10’s of ms [6]. Therefore, conventional pulse-burst laser (PBL) systems are not suitable for investigation of turbulent combustion over such a broad range of time scales.

In recent work, the authors have developed a quasi-continuous burst-mode laser (QCBML) that extends the burst duration to 10 ms, an order of magnitude improvement over previous designs [22]. In this laser a pulsed fiber-based master oscillator output is amplified through the hybrid amplifier chain with initial stages based on three diode-pumped Nd:YAG amplifiers and a final stage based on an extended-duration, low-gain flashlamp-pumped Nd:YAG amplifier. Because of the advantages of the fiber master oscillator and highly efficient, high-gain diode-pumped amplifiers, the QCBML employed only four amplifiers with a laser optical footprint of only 0.56 m$^2$ and low electrical power consumption of ~1 kW, which is similar to the power consumption of a standard high-pulse-energy, 10-Hz Nd:YAG laser. This system increased the duration of previously published burst-mode laser sequences by nearly tenfold with sufficient energy in a burst of 200 pulses to perform 20-kHz formaldehyde PLIF for the first time in a lifted methane–air diffusion flame. Subsequently, Fuest et al. demonstrated a 10-kHz, 10-ms burst duration PBL system with up to 200 J per burst based on a solid-state pulsed master oscillator amplified through a chain of eight flashlamp amplifiers [24], although its utility for planar measurements was not evaluated.

While high-power, 10-ms-long burst durations open a variety of applications for PBL systems, it is of interest to further extend the burst sequence to study many low-frequency processes, including flame instabilities due to acoustic noise [25], blowout processes [26], and chemical kinetics–driven instabilities [27], which have characteristic frequencies as low as 20 Hz. Therefore, another order of magnitude increase in burst duration up to 100 ms is desirable to capture the full range of frequencies in reacting flows of practical interest.

Because high discharge energy expected for burst durations of up to 100 ms results in fast degradation of flashlamp lifetime [28], it is of interest to replace flashlamp-pumped amplifiers by diode-pumped amplifiers, which have about tenfold the electrical-to-optical efficiency. However, to the best of the authors’ knowledge, there are no data available for diode-bar life expectancy at pulse durations longer than a few ms. Because of the high cost of diode bars, it is also important to evaluate the diode-bar performance at such conditions. Additionally, while 10-ms burst durations result in a fairly uniform pulse sequence in time, long sequences of 10’s of ms could trigger a change in the temperature-dependent characteristics of the diode bars and lead to thermal gradients in the amplifier rods. Data on the evolution of beam profile for burst-mode lasers are not currently available, but such data are instrumental for extending the pulse durations of next-generation systems.

To address the aforementioned issues, we demonstrate an all-diode-pumped, QCBML with an unprecedented burst duration of 30 ms and show its utility for PLIF of formaldehyde using the frequency-tripled output at 354.8 nm. We furthermore evaluate the effects of burst duration on the spatial mode, explore a range of repetition rates, provide the first life-test data for long-pulse operation of different types of diode bars, and discuss the advantages and potential limitations of diode-bar amplifiers for burst-mode laser design.
2. Experimental setup

The all-diode-pumped QCBML layout is shown in Fig. 1(a). A commercial pulsed Yb-doped fiber laser generates a continuous 100-kHz train of pulses at 1064.3-nm wavelength with per-pulse energy of 10 µJ. The fiber-laser pulse duration is 13 ns, and the linewidth is less than 2 GHz. The utilization of a polarization-maintaining single-mode fiber results in a Gaussian beam profile with an M$^2$ factor of 1.3. To control the pulse-train repetition rate, the output of the fiber is collimated and directed into a pulse picker based on a 1-MHz bandwidth EOM. The EOM is used in a double-pass configuration along with an optical isolator (see Fig. 1(a)), resulting in an extinction ratio of 2×10$^3$. This high extinction ratio serves to completely suppress ASE from the fiber laser so that the pulse train can be effectively amplified to a high level within the amplifier chain.

The burst from the fiber amplifier is then passed through a spatial filter before being amplified in two 2-mm-diameter Nd:YAG-rod diode-pumped amplifiers. To prevent build-up of ASE from the diode amplifiers, a relay optical arrangement with a spatial filter is placed between the amplifiers. To compensate for thermally induced birefringence, a quartz rotator is placed between the two amplifiers. The total gain of the first two amplifier stages reaches 10$^3$ with output pulse energy of 4 mJ. In order to maximize the energy extraction, we use a third 5-mm-diameter Nd:YAG-rod diode-pumped amplifier in a double-pass configuration, as shown in Fig. 1(a). The third amplifier single-pass and double-pass gain dependence on driving current is shown in Fig. 1(b) for a 10-kHz burst with 1-mJ input pulse energy. The amplifier is separated from the initial two stages by an optical isolator and a spatial filter to avoid feedback and reduce build-up of ASE. In order to further reduce ASE, the first pass is relay imaged back to the amplifier with a spatial filter inserted in the focal plane of the relay optics. Because of the high pulse energy after a single pass, a spatial filter is installed inside a custom vacuum cell to prevent air ionization in the beam focus. The amplifiers are fired at 0.25-Hz repetition rate to allow thermal relaxation of the Nd:YAG rods.

Finally, the fundamental output is converted via third-harmonic generation (THG) to 354.8 nm by using two LBO Type I crystals for doubling and tripling, respectively. The first LBO crystal (used in the noncritical phase-matching configuration) is placed in an oven heated to
149.7 °C. The second crystal is heated to 60 °C to increase damage threshold and obtain stable phase matching. To control the fundamental beam polarization for optimal THG generation, a dual-wavelength waveplate (λ/2 for 532 nm, λ for 1064 nm) is used between the two nonlinear crystals. The dependence of 1064-nm pulse energy on repetition rate is shown in Fig. 1(c).

To test durability of the diode bars at long-driving-pulse conditions, we evaluated three types of AlGaAs bars: continuous wave (CW), quasi-continuous wave (QCW), and special-package QCW diode bars. CW bars have a 1.2-mm resonator length and 50 emitters per bar, each of which is 100 µm wide. QCW bars have a 1-mm resonator length and 52 emitters per bar, each of which is 150 µm wide. In the special-package QCW bars, indium solder bonds are replaced with AuSn.

To monitor the evolution of the beam profile, high-speed, single-pulse beam profiling was performed using 1% of the fundamental beam, which is expanded to 25 mm and projected onto a white screen. A Photron SA5 camera was synchronized with the QCBML, and high-resolution images of each pulse profile were recorded. Image pixels were binned 2×2 to reduce speckle, and horizontal and vertical profiles were averaged and fit to a Gaussian line shape. The beam diameter (1/e²) was calculated from fit parameters and known magnification.

3. Results and discussion

To address the long-pulse life expectancy of the three types of AlGaAs diode bars, n = 6 bars were tested for over 2 million pulses each with drive currents of 50 A and 70 A and pulse widths of 5 ms and 15 ms. Figure 2 shows the output power for each sample and condition. All samples (with one exception) fared well through the 70-A, 15-ms step. The special-package QCW was screened out during burn-in as it failed because of manufacturing defects. The post-test microscope inspection of all samples showed no evidence of solder creep, which is the major degradation pathway due to thermal stress from long driving current pulses. Because of time constrains, only ~0.5 million pulses were fired at each test condition, with a total of over 2 million pulses. However, because of the low burst-repetition rate of the QCBML (0.25 Hz), this corresponds to over 2000 hours of operation. Since no degradation was observed, we anticipate up to an order of magnitude longer life time than that tested.

Parameter optimization for long-pulse diode-pumped amplifier operation was established by evaluating the temporal profile of the stored energy in the Nd:YAG rod. Since the stored energy inside the Nd:YAG rod is released either as heat or spontaneous emission, it can be evaluated by observing the intensity of spontaneous emission. Figure 3 shows the drive current and temperature dependence of spontaneous emission from the 5-mm-diameter Nd:YAG amplifier pumped with a 50-ms driving pulse. Temperature-induced shift of the emission wavelength (0.3 nm/K) as the diode-bar temperature rises during the long drive pulse can shift the emission peak off the maximum absorption wavelength of Nd:YAG at 808
nm. By optimizing the temperature of the diode-bar cooling water, the initial emission wavelength can be controlled. At low current, as shown in Fig. 3(a), the temperature change is small and the energy pumped into the rod is nearly constant (10% change for 30°C curve). As the current increases, the amount of pumped energy drops with time; at the highest current of 80 A, as shown in Fig. 3(e), the efficient pumping window shrinks to ~10 ms. By lowering the cooling-water temperature from 30°C to 20°C, the uniform emission window is extended up to 40 ms at 60-A drive-pulse current, as shown in Fig. 3(c).

A second important characteristic is beam size and shape. To date, few details on the shot-to-shot fluctuations of beam quality have been reported for burst-mode laser systems. Of particular interest is the evolution of these characteristics over the relatively long burst durations of next-generation systems (>10 ms). To analyze this effect, we imaged the beam intensity distribution at 10 kHz, allowing pulse-to-pulse variations to be characterized. The change in beam profile for a single 20-ms burst is shown in Fig. 4 at several points in time.

Note that the beam-profile change is not a simple change in size as one would expect from a thermal lensing effect. Instead, the beam-profile change is also partially induced by the change in flux of the diode-bar radiation throughout the rod cross section. This change in flux produces a complex gain profile across the rod, which is manifested in a pentagonal shape of the beam at burst durations longer than 10 ms. The evolution of the diode-bar illumination pattern is due to shifting of the emission wavelength from the absorption maximum of...
Nd:YAG as discussed above and can be alleviated through proper selection of the diode-bar initial temperature and driving current.

Both temperature and diode-current conditions for long-pulse operation of the diode-pumped amplifiers were determined by evaluation of intensity and beam diameter for each pulse in the burst sequence. Figure 5 summarizes the time dependence of the 1064-nm-output pulse intensities and diameters at different cooling-water temperatures and drive-pulse currents. The immediate onset of variation in the beam diameter cannot be explained by the thermal gradient induced by heat diffusion from the central part of the rod to the cold outer layer. The onset of the thermal gradient depends on the thermal time constant of the rods, which for 2-mm- and 5-mm-diameter rods are calculated to be 0.2 s and 1.25 s, respectively, much longer than the duration of the burst [29]. Instead, we attribute the observed change in beam diameter over time to the instantaneous thermal gradient due to absorption of the diode-bar radiation, which is partially converted to heat.

To qualitatively understand the observed change of beam diameter with time shown in Figs. 5(a) and 5(b), we can consider two extreme conditions. The first is with the diode-bar emission at the peak of the absorption of Nd:YAG. In this case the outer layer strongly absorbs radiation from the diode bar and is heated to a higher temperature compared to the central part of the rod, thus producing a negative lensing effect [30, 31]. The second is with the diode-bar emission shifted from the absorption peak. In that case the diode-bar radiation is absorbed less by the outer layer and is concentrated in the center, producing a positive lensing effect. In the experimental data of Figs. 5(a) and 5(b), the initial temperature of the rod and the current both affect the time profile of the beam diameter. At a cooling-water temperature of 20°C, the diode bar initial wavelength is blue shifted from the absorption maximum. At low driving current, the initial beam diameter slightly increases for several ms and, after reaching a maximum value, rapidly drops, reaching a minimum after 20 ms, as shown in Fig. 5(a). The change in beam diameter is more profound at higher driving current. For 30°C cooling water, the diode-bar output is at the absorption maximum of the Nd:YAG, and time profiles for all driving currents start from a maximum value and drop to a minimum at ~15 ms, as shown in Fig. 5(b). The corresponding intensity profiles for 20°C and 30°C cooling-water temperatures are shown in Figs. 5(c) and 5(d), respectively. Similar to the diameter profiles, the 20°C intensity-profile maximum is shifted beyond the 10-ms burst duration, while the 30°C intensity profile exhibits a maximum intensity at only a few ms. In contrast to the fast change
in beam diameter with time, the pulse-intensity profile is flatter. Even though the diode-bar absorption pattern changes, most of the emission is absorbed and extracted by the pulse train.

Given these performance characteristics, it is of interest to evaluate the feasibility of using the current three-amplifier design for planar fluorescence imaging. Based on analysis of the data shown in Fig. 5 and adjustments to the cooling water, an optimized temperature of 29°C was selected with a drive current of 45 A for the first two amplifiers and 60 A for the third amplifier, as shown by the red curves in Figs. 5(b) and 5(d). These parameters were used to generate up to 30 mJ pulse energy at 354.8 nm over a 30-ms burst duration, which captures transients that evolve over a longer time period than those observable with the 10-ms bursts achieved in previous work [22, 24]. In this case the repetition rate was reduced to 5 kHz in order to maintain sufficient pulse energy near the end of the burst, as shown in Fig. 5(d). The system performance was demonstrated by high-speed planar laser-induced fluorescence imaging of formaldehyde (CH₂O) in a CH₄–H₂–N₂ jet diffusion flame with jet diameter of 2 mm and Reynolds number of 8800. The fuel is 22.1% CH₄, 33.2% H₂, and 44.7% N₂ by volume. Formaldehyde excitation was performed at 354.8 nm, the third-harmonic output of the QCBML, and fluorescence was detected using a high-speed CMOS camera with a dual-stage intensifier as described in prior work [22]. The benefit of the 30-ms burst is evident in the periodic shedding of the flame layer, shown in Fig. 6, where nearly three full periods of flame pinch off are observed (frames 36–72, 72–90, and 90–135). The sequence also illustrates the varied flame structures and dynamics of the stabilization region for lifted jet diffusion flames. The images in Fig. 6 are not corrected for spatial variations in the beam profile or shot-to-shot energy variations, although this has been shown to be relatively straightforward in previous work on burst-mode PLIF [22].

![Fig. 6. Direct photograph (left) and 30-ms-duration PLIF imaging of CH₂O in a lifted CH₄–air diffusion flame at 5 kHz showing every third image (right). False-color scales indicate non-normalized, background-subtracted camera counts. The full sequence is available online as Media 2. The field of view is indicated on the photograph by the dashed line.](image-url)
From the data in Fig. 6, the signal-to-noise ratio (SNR) varies from a minimum of 6 at the beginning of the sequence to 40 at the middle of the 30-ms sequence. This minimum is greater than some burst-mode PLIF work with durations of only 1 ms [18] and should be useful for studies of turbulent combustion dynamics.

The system can be easily expanded to higher energy per pulse by adding larger diode-pumped amplifiers to the three that were used in the current work. For example, a diode-pumped Nd:YAG amplifier with a 188-mm-long, 10-mm-diameter rod can be pumped with up to 36 kW peak power. For 100-µs separation between pulses in a 10-kHz burst, this corresponds to 3.6 J. Ideally as high as 40% of this energy can be converted to 1064-nm output, which corresponds to 1.4 J per pulse. Considering a fill factor of 0.6, one can obtain up to 0.9 J per pulse. By adding more amplifiers the energy per pulse can be increased until it reaches the Nd:YAG damage threshold of 15 J/cm² (for an uncoated, 10-mm-diameter rod). Additional increases in pulse energy can be accomplished with further increases in the rod diameter.

4. Conclusions and outlook

In the current work we increase the burst duration achieved with previous diode-bar- and flashlamp-pumped PBL systems by three times to 30 ms by utilizing two single-pass and one double-pass diode-pumped amplifiers. The lifetime test data for three types of diode bars showed no degradation for long driving-pulse durations with over two million pulses, indicating the feasibility of diode pumping for long burst durations. Extension of the burst duration from 10 ms to 30 ms was accomplished with no modifications to standard power supplies or diode-bar drivers. Because of the high efficiency of diode-bar amplifiers, the extended-duration PBL laser maintained a relatively small spatial footprint and compact power supply while achieving 1064.3-nm output energies of 120 mJ/pulse at 10 kHz. This was sufficient for efficient frequency conversion to 354.8 nm for use in high-speed formaldehyde PLIF imaging to capture vortex-flame interactions over several cycles in a lifted CH₄-air jet diffusion flame. The ~30% conversion efficiency to third harmonic in combination with high beam quality makes this system a potential pump source for optical parametric oscillators, and the burst-mode operation would allow high-speed pumping of dye lasers without rapid degradation of the dye. Hence, the novel laser system fills the gap between high-average-power, kHz-rate continuously pulsed systems and short-duration PBL systems. With further improvement, the QCBML architecture can become a unique tool to study both low-frequency instabilities and high-speed flow dynamics. A key area for improvement is minimizing the shift of the diode-bar emission wavelength for long burst durations and high driving current. This shift was identified as a major cause of degradation in beam quality and a decrease in both beam diameter and pulse intensity within long bursts. For the current design, the degradation in beam quality beyond 30 ms limits further extension of the burst duration. However, this limitation can be overcome by utilizing wavelength-stabilization elements in the diode-bar design, which is the subject of future work.

Acknowledgments

The authors are grateful to C. Dedic of Iowa State University for technical assistance. This work was funded by the Air Force Office of Scientific Research (Dr. Chiping Li, Program Manager) and the AFRL under contract No. FA8650-12-C-2200.