

Simple method enabling pulse on command from high power, high frequency lasers

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A method for addressing individual laser pulses in high repetition frequency systems using an intracavity optical chopper and novel electronic timing system is reported. This “pulse on command” capability is shown to enable free running and both subharmonic pulse rate and burst mode operation of a high power, high pulse frequency copper vapor laser while maintaining a fixed output pulse energy. We demonstrate that this technique can be used to improve feature finish when laser micromachining metal. © 2006 American Institute of Physics. [DOI: 10.1063/1.2338284]

I. INTRODUCTION

High average power lasers, incorporating high pulse energy (>1 mJ) with high pulse repetition frequencies (>100 Hz), are used in industrial applications ranging from precision laser micromachining to high speed photography and velocimetry. The primary types of lasers falling into this category are Q -switched Nd:YAG (yttrium aluminum garnet), copper vapor, and excimer lasers.

Detailed studies of laser induced material removal¹ have shown that pulse repetition frequency plays a significant role in precision laser micromachining. In particular, high pulse repetition frequencies can lead to cumulative heating of target substrates which increases material removal rates but reduces feature resolution.² As a result, low pulse repetition frequencies of <1 kHz are preferred for precision laser micromachining applications whereas high pulse rate systems are better suited to low resolution cutting and drilling. Similarly, low pulse rates are preferred when processing substrates such as ceramics that are sensitive to bulk damage due to thermal shock.³ Additionally, pulse on command improves process control when micro-machining complex shapes and laser milling, and pulse bursting is an important factor determining the dynamic range for high speed photography and velocimetry.⁴

High average power lasers such as Q -switched Nd:YAG and copper vapor are most commonly constrained to operating at fixed pulse repetition frequencies and thus do not offer the flexibility required of many laser applications. For example, Q -switched Nd:YAG lasers are optimized by balancing output power performance against internal thermal loading of the laser crystal.⁵ In the case of metal vapor lasers such as copper vapor lasers, the copper ground state and upper laser level populations are influenced by the laser tube temperature.⁶⁻⁸ The thermal mass of a typical copper laser plasma tube will permit transient changes to the pulse rate before the laser tube temperature significantly changes; how-

ever, the altered prepulse plasma conditions result in large variations in the output pulse energy. These limitations can be overcome by employing master-oscillator-power-amplifier configurations that manipulate the relative timing between two lasers operating at a fixed pulse repetition frequency to deliver output pulse trains ranging from 1 Hz to several kilohertz;^{9,10} however, these systems come with an increased cost and larger footprint. In this article we report a new method for achieving dynamic control of the output pulse frequency of a single oscillator using an intracavity optical chopper and novel timing system. Briefly, the laser is synchronized to an intracavity chopper and laser pulses are either blocked (zero delay) or transmitted by applying pulse selectable delays to the laser trigger, while leaving the gain medium relatively unperturbed. Using this configuration, we have operated a 6 kHz copper vapor laser in single pulse, burst, and continuously pulsed modes over frequencies ranging from 1 Hz up to 6 kHz.

II. EXPERIMENT

The laser used in these experiments was a high temperature copper vapor laser (CVL) with a 25 mm diameter, 1 m long active region. The excitation circuit for the CVL consists of two stages of magnetic pulse compression and is switched using a hydrogen thyratron (Perkin Elmer HY3001). The nominal pulse repetition frequency and average output power (when operating with a plane-plane resonator) of the laser are 6 kHz and 20 W, respectively. For these experiments, the laser was operated with a folded positive branched unstable resonator comprising a 50 mm diameter rear high reflector [radius of curvature (ROC)=2 m], an on-axis elliptical [diameter of 2×1 mm²] spot scraper mirror, and a feedback mirror (ROC=50 mm).

A custom designed intracavity optical chopper wheel was placed at the common foci of the curved mirrors as shown in Fig. 1. The chopper wheel apertures, consisting of a 100 mm diameter track of 100 slits (of width of 250 μ m), were aligned with the optical axis of the laser and the wheel was driven using a Stanford Research Systems SR540 chop-

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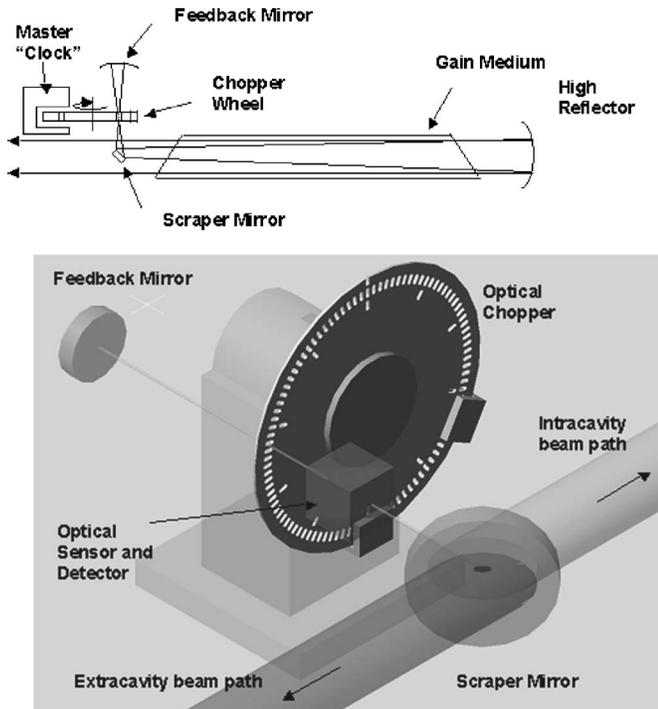


FIG. 1. Schematic of the laser resonator and intracavity chopper system. Inset shows a detailed view of the intracavity chopper, scraper mirror, and feedback mirror.

per driver. An additional gate photodiode was fitted to the chopper wheel to monitor the phase of the track containing the 100 slits. The master clock for the CVL trigger circuit was derived from this track, the chopper wheel being rotated at 60 rps. This master clock was used as the external trigger for a delay generator and a programmable N -shot controller built in-house. The delay generator was used to produce two delayed replicas of the master clock as shown in Fig. 2. One of these replicas (the “on” pulse) corresponded to synchronously triggering the laser pulse timing to a hole in the chopper wheel and therefore completing the laser cavity; the other (the “off” pulse) corresponded to synchronizing the laser pulse timing such that the laser cavity is blocked. These two delays and the master clock were then fed to the N -shot controller. This controller was used to select between the on and off pulses either continuously (acting much like a shut-

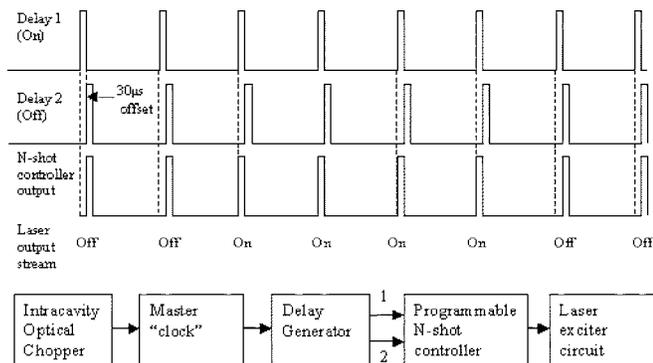


FIG. 2. Schematic of the timing circuit. The master clock triggers the delay generator to produce two transistor-transistor logic (TTL) pulse trains offset by $30 \mu\text{s}$. The programmable N -shot controller selects from these and triggers the laser exciter.

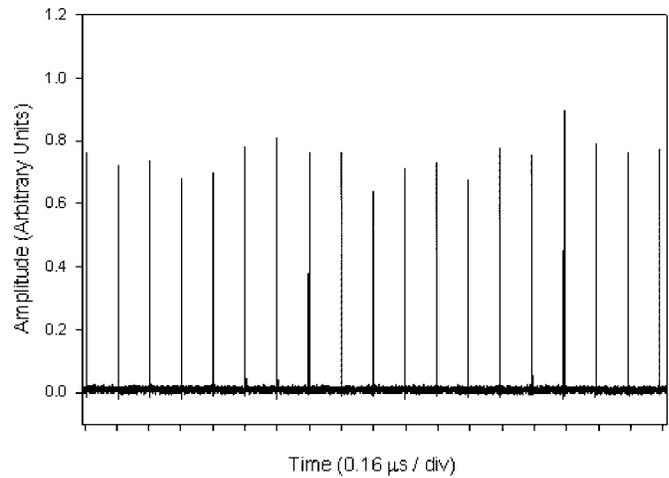


FIG. 3. Oscilloscope data showing the laser output pulse train when the laser is triggered with “zero” delay.

ter) or for a desired number of pulses at a prescribed frequency (to produce an N -shot pulse burst). Typically the difference between the on and off pulses was $30 \mu\text{s}$; therefore selecting between the two pulses represented a timing jitter of approximately 20%, an amount not sufficient to cause upset to the exciter circuit. Although only a single delay channel is necessary for this system, it was convenient to use two adjustable delays because this removed the need for accurate positioning of the chopper wheel’s rotational angle with respect to the optical axis. Once positioned in the laser cavity, the position of the wheel’s slits was readily controlled by adjusting the pulse generator delay.

The output characteristics of the laser were investigated using a fast photodiode coupled to an oscilloscope (Tektronix 3054B). The output beam was sampled within 1 m of the laser to ensure that both the amplified spontaneous emission (ASE) and the high beam quality laser pulses were within the photodiode’s dynamic range. This was not possible at distances >1 m due to the ASE’s high divergence. Micromachining studies were performed using computer controlled translation stages (Aerotech ATS100 series) situated ~ 2.5 m from the laser and analyzed using optical microscopy.

III. RESULTS AND DISCUSSION

Figure 3 shows the oscilloscope data for a 6 kHz optical pulse train when the delay generator was fixed in the on condition and the laser was free running. Note that the variability in the amplitude of the output pulses is due to the limited sampling speed of the oscilloscope when monitoring long time scales. The pulse to pulse stability was actually measured to be $\pm 2\%$ which is the same as that when the copper vapor laser was operating without the intracavity pulse picker.

Figures 4 and 5 demonstrate the dynamic control available using the optical pulse picker. In the case of Fig. 4 we have reproduced the raw information displayed on the oscilloscope screen for comparative purposes. Once again the limited sampling speed of the oscilloscope introduced variability in the recorded laser pulse amplitude. In detail, Fig. 4 shows the laser making the transition from the off condition,

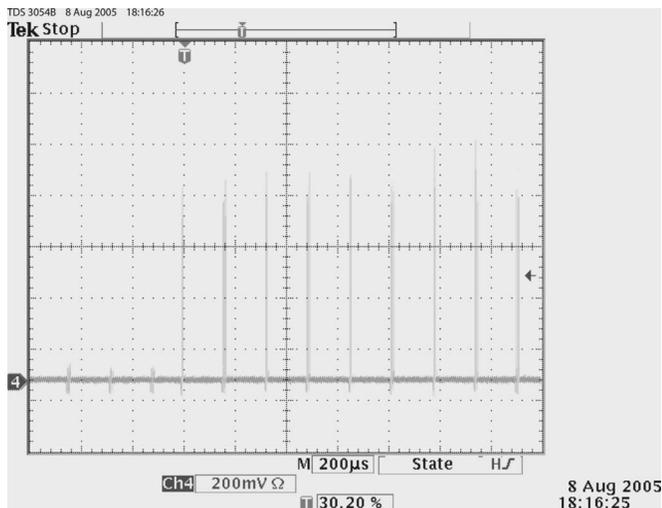


FIG. 4. Replica of the oscilloscope screen showing the laser output pulse train when the laser has toggled from the “off” to “on” mode.

where the optical output train consists entirely of ASE, to the on condition consisting of stimulated emission. In Fig. 5 the laser is operated in a burst mode, whereby the electronic output of the delay generator is set for a repeating set of three on pulses followed by three off pulses. In both examples the small $30 \mu\text{s}$ timing offset between the on and off conditions is evident. Alternatively, the laser can be configured to produce optical output trains at subharmonics of the free running frequency ranging from kilohertz to hertz. Figure 6 shows a set of optical pulses captured when the laser was operating at 3, 1.5, 0.6, 0.3, and 0.06 kHz, demonstrating good pulse energy stability as the optical output train is dynamically controlled over this range of frequencies. It is important to note that the temporal forms of these output pulses are also the same, indicating that the beam quality has been preserved as the laser ranges between 60 Hz and 3 kHz.

The intracavity chopper and associated timing system overcome the limitations of using external beam shutters to control the laser output train. For example, the fastest a reed shutter can open and close is approximately 50 ms. The minimum number of pulses that can be addressed with this

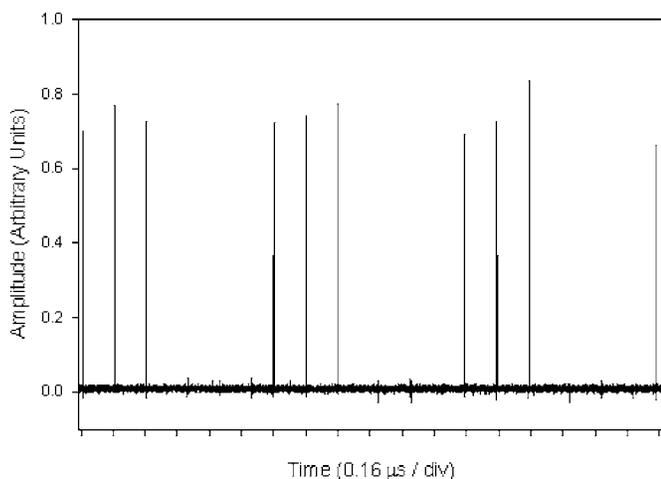


FIG. 5. Oscilloscope data showing the laser output pulse train when the laser is operating in burst mode.

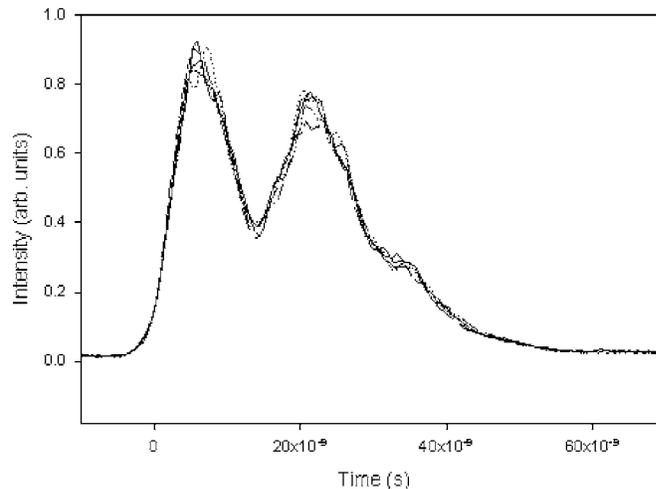


FIG. 6. Laser pulse shapes for the laser running at subharmonic frequencies ranging from 3 kHz to 60 Hz.

type of shutter is of the order of hundreds when used with lasers operating at pulse rates in the kilohertz range. The reed shutter during the 50 ms on/off transition also causes vignetting of the pulse train. Single pulses and short pulse bursts can be produced by interrupting the excitation circuit for milliseconds or more to enable the external reed shutter to fully open or close. However, the first output pulse produced by the laser can have two to three times the energy of subsequent pulses and the CVL plasma can detrimentally cool if this pulse control method is used repeatedly. By comparison, the dynamic control offered by the intracavity chopper and timing system can address laser pulses on an individual basis without negligible perturbation to the laser’s steady state gain properties. This type of control, available from a single laser oscillator, is generally reserved for relatively complex master-oscillator-power-amplifier systems⁹ that require two laser elements with an associated larger footprint.

The $30 \mu\text{s}$ timing offset used to control the output pulse train reduces the interpulse period by 20%. This reduction in the plasma relaxation time causes a small reduction in the optical gain available to the first on pulse (as reported in Ref. 8). By contrast, optical feedback, or lack thereof, has been shown to have a negligible influence on CVL gain characteristics. As a result of the reduced gain, the first pulse of a burst of laser pulses has slightly lower energy than that of the subsequent pulses in the train, as shown in Fig. 7. In this case the first pulse was measured to have 12% less energy than subsequent output pulses, however, this change in pulse energy is significantly smaller than that produced by other pulse control methods where the laser excitation circuit is interrupted for milliseconds or more. For most applications this transient change in pulse energy is not significant; however, it can be suppressed by rotating the chopper at faster rates or using tighter intracavity focusing geometries such that the timing offset required to interrupt optical feedback to the gain medium is minimized. Conversely, the timing offset can be added to the interpulse period to produce a first pulse with slightly higher pulse energy.

The first pulse behavior noted above is analogous to the large first pulse produced by high power Q -switched solid

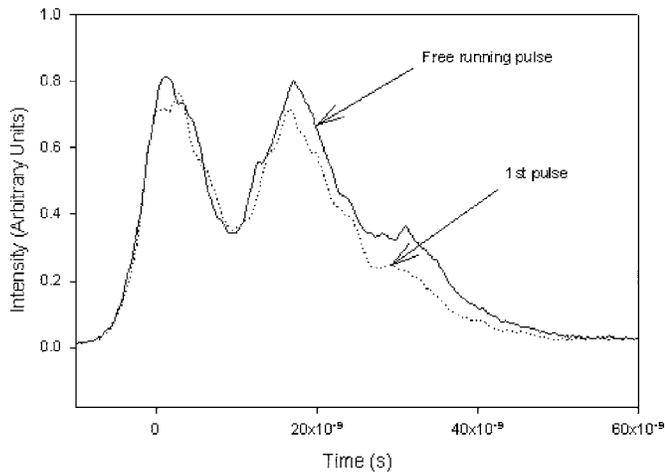


FIG. 7. Comparison between a free running pulse shape and the first pulse in a pulse train when the laser is toggled between the “off” and “on” conditions.

state lasers at the beginning of an output pulse train. However, in solid state lasers, the enhanced first output pulse is due to increased storage within the gain medium. As a result, many commercial laser systems employ electronic techniques to suppress the first pulse by controlling an intracavity acousto-optic modulator. The pulse-on-command method may be used as an alternative to electronic suppression in cases where there are tight constraints on the energy and the spatiotemporal characteristics of the first pulse, as it does not directly interfere with the energy dynamics in the laser resonator.

The dynamic control available with our system has implications for many laser applications requiring good pulse control. Figure 8 shows micrographs of the corner of rectangular features laser machined in 100 μm brass shim with the

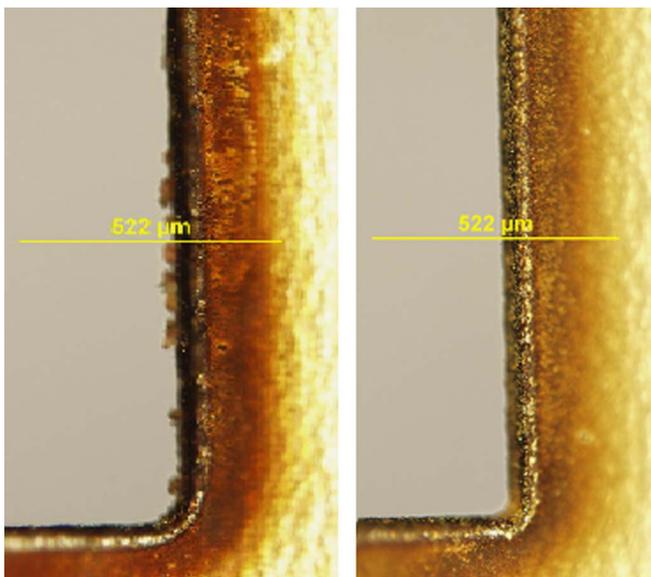


FIG. 8. (Color online) Micrographs of the corner of a rectangular features micromachined in brass shim. The left-hand and right-hand examples have been processed with optical pulse trains at frequencies of 6 kHz and 600 Hz, respectively.

copper vapor laser producing 6 W of average power (at 6 kHz) and focused onto the target samples using an achromatic lens ($f=100$ mm) and a translation speed of 100 mm/min. The pulse on command was configured to produce laser pulse trains of 6 kHz and 600 Hz, respectively, for the two cases. Note that in order to expose the samples to the same total amount of energy in the 600 Hz case, the sample was exposed to ten times as many passes as that used for the 6 kHz case. The ASE incident on target was also negligible. The brass shim machined at the laser’s free running frequency of 6 kHz has a significant heat affected zone (HAZ) and poor edge quality. By comparison, the sample machined at low pulse rate exhibits reduced HAZ and improved edge quality. The corner is also better defined in the latter case as a consequence of improved thermal management. Pulse control of this type is also important for direct-write laser photolithography where it is important to maintain constant exposure when scanning the laser beam across a photoresist at different velocities, especially when accelerating and decelerating motion control stages through 90° bends in complex designs. This method also has implications for high speed imaging and velocimetry because high intensity laser pulse pairs can be delivered at delays that are any multiple of the interpulse period.

Pulse on command is readily available in hertz pulse rate lasers by the movement of an optical element into and out of the beam path. However, this solution is not possible for kilohertz pulse rate laser systems because fast actuators cannot move these elements on a time scale shorter than the interpulse period (typically <1 ms). The alternative is to put these optical elements in continuous motion and control the relative phase with which the laser is triggered. This technique, shown here to produce pulse on command for a 6 kHz copper vapor laser, can offer other forms of dynamic control via the introduction of other optical elements on the wheel such as polarizing and wavelength filters, slits, and apertures.

IV. SUMMARY

We report, for the first time, a novel pulse control method that uses an intracavity chopper and timing system to control the pulse rate and phase of the excitation circuit of a high pulse rate, high power copper vapor laser. This system produces pulses on command by addressing each laser pulse on an individual basis. This simple method, which can be retrofitted to most laser types in an extracavity format, has implications for laser applications requiring good pulse control such as laser micromachining, direct-write photolithography, and high speed imaging.

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¹F. C. Burns and S. R. Cain, *J. Appl. Phys.* **29**, 1349 (1996).

²E. K. Illy, D. J. W. Brown, M. J. Withford, and J. A. Piper, *IEEE J. Sel. Top. Quantum Electron.* **5**, 1543 (1999).

³J. Pascual-Cosp, A. J. Ramirez del Valle, J. Garcia-Fortea, and P. J. Sanchez-Soto, *Mater. Lett.* **55**, 274 (2002).

⁴I. Grant, *Proc. Inst. Mech. Eng., Part C: J. Mech. Eng. Sci.* **211**, 55

- (1997).
- ⁵H. Jing-ya, *J. Appl. Phys.* **54**, 2214 (1983).
- ⁶M. J. Kushner, *IEEE J. Quantum Electron.* **17**, 1555 (1981).
- ⁷R. J. Carman, R. P. Mildren, M. J. Withford, D. J. W. Brown, and J. A. Piper, *IEEE J. Quantum Electron.* **36**, 438 (2000).
- ⁸R. P. Mildren, M. J. Withford, D. J. W. Brown, R. J. Carman, and J. A. Piper, *IEEE J. Quantum Electron.* **34**, 2275 (1998).
- ⁹C. Körner, R. Mayerhofer, M. Hartmann, and H. W. Bergmann, *Appl. Phys. A: Mater. Sci. Process.* **63**, 123 (1996).
- ¹⁰D. J. W. Brown and M. J. Withford, *Opt. Lett.* **26**, 1885 (2001).