High-energy pulse-burst laser system for megahertz-rate flow visualization

Pingfan P. Wu and Richard B. Miles

Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, New Jersey 08544

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A high-pulse-energy megahertz-repetition-rate Nd:YAG-based pulse-burst laser system has been developed. The laser can produce a burst of more than 30 pulses, with an average energy per pulse of 70 mJ, at up to 1-MHz repetition rate. The burst repetition rate is 9 Hz. Coupled with a megahertz-framing-rate CCD camera, the frequency-doubled pulse-burst laser system has been successfully used in the visualization of shock evolution in a supersonic flow. © 2000 Optical Society of America

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Many aspects of supersonic and hypersonic flow are poorly understood, because the experimental database on them is small and their physical picture is unclear. One problem facing the experimental fluid mechanics field is that a supersonic flow evolves very rapidly. Freezing a supersonic flow event requires measurements with a sample time less than tens of nanoseconds. Single- or double-pulse Q-switched Nd:YAG lasers have been used to freeze motion at one or two instants.[1] Single- or double-pulse imaging works well if a full time history is not required or if the events are reproducible enough for valid data to be obtained from repeated experiments. In many cases, such as turbulent flow, the evolution is not repeatable, and a rapid sequence of images is required for an understanding of the dynamics. It is difficult to record such a sequence when the interframe time required is microseconds, which is the characteristic time of hypersonic flow evolution.[2] The megahertz- (MHz-) rate laser has been developed to rapidly sample and freeze individual frames with short high-energy pulses and produce a full-time history of the relevant flow evolution through a sequence of these short pulses.

One approach to constructing a MHz laser system is to have a multilaser system with the lasers set at delays of microseconds with respect one another. For example, Theocaris *et al.* built a system employing 16 single-shot ruby lasers.[3] Kaminski *et al.* used four independent double-pulse Nd:YAG lasers to take eight sequential pictures.[4] These multilaser systems require very careful alignment so that all beams overlap properly and share the same mode structure.

The other approach is a single-light-path, multiple-pulse laser system. A continuously running, single-path, high-repetition-rate pulsed laser system would, in principle, be the best choice. However, the total output power of the laser is constrained by the thermal loading that the lasing elements can tolerate. For a continuous-duty-cycle laser system, the single-pulse energy decreases as the pulse repetition rate increases. For example, the current maximum power for a commercially available pulsed Nd:YAG system is approximately tens of watts at 1.06 μm. This means that, if the MHz-rate pulse laser were run as a continuous-duty-cycle system, thermal considerations alone would limit the output energy to approximately tens of microjoules per pulse. This energy is a thousand times too low to be generally useful for flow-imaging experiments. The key to boosting the single-pulse energy is to reduce the duty cycle and operate in a pulse-burst mode. An example of a pulse burst can be seen in Fig. 1: In each burst, tens of pulses are generated (in this figure only four pulses are shown). The repetition rate of the pulses in the burst is variable up to 1 MHz, but there are only ten bursts or so per second. Consequently, the laser in pulse-burst mode can have both a high repetition rate and high single-pulse energy. The fact that a continuous data stream is not available means that long-time-scale fluctuations are not recorded. This is usually not a problem, since the flow has by then moved out of the field of view of the camera. One example of a laser in pulse-burst mode is a repetitively Q-switched ruby laser,[5,6] which can operate reliably at up to 500 kHz.[5] Another example is the MHz-rate pulse-burst laser system.

The prototype pulse-burst laser[7] could generate ~10 mJ of energy per pulse at 1.06 μm at a 1-MHz repetition rate. This Letter describes a new generation pulse-burst laser. The design goal was a MHz-repetition-rate laser system with at least 30 pulses per burst, more than 50 mJ of energy per pulse at 1.06 μm, and tens of millijoules of energy at 0.532 μm, so that the laser can be used as an illumination source for flow-imaging experiments.

Figure 2 illustrates a generic diagram of the laser system, which is in a master oscillator and power amplifier architecture. The laser is composed of four major parts: a cw master oscillator, a pulse slicer to chop

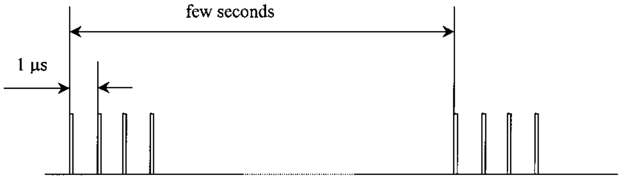

Fig. 1. Example of a pulse burst.

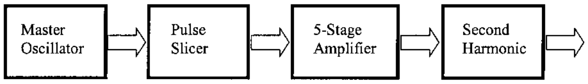

Fig. 2. Generic pulse-burst laser system.

the cw light and generate a pulse burst, a five-stage amplifier, and a second-harmonic crystal.

Figure 3 is a detailed schematic diagram of the system. The master oscillator is a narrow-linewidth diode-pumped cw Nd:YAG laser (Lightwave Electronics 124) with 50-mW output. The pulse slicer is a pair of custom-built (Medox, Ann Arbor, Mich.) Pockels cells, which are similar to those used as Q switches for a standard solid-state laser system. The cw light from the master oscillator is first amplified and then reflected by a thin-film polarizer (TFP2) to the Pockels cells. When one Pockels cell is on, the polarization of light is changed by $\pi/2$ in a double pass, and light is transmitted through TFP2 into Amplifier #2. When both or neither of the Pockels cells are on, the polarization of the beam stays unchanged, so the return beam is reflected back by TFP2 and blocked by an optical isolator. By switching of the Pockels cells in MHz-rate pulse-burst mode, a MHz-repetition-rate pulse burst is transmitted through TFP2. Charging a Pockels cell takes a few nanoseconds, but discharging it takes ~50 ns. If only one Pockels cell were used to chop the light, the falling edge of a single pulse could be 50 ns long. So two Pockels cells are used to shape the pulse: They are switched with a minimum separation of 10 ns and discharged simultaneously, so there is a controllable transmission window that determines the pulse length.

There are five amplifier stages in the system. The Nd:YAG rod diameters are 6.5, 6.5, 8, 9.5, and 12.7 mm. The lengths of all the rods are 110 mm. Amplifier #1 is four pass. Amplified spontaneous emission is minimized by placement of Amplifier #1 in front of the pulse slicer. In this stage the power remains below saturation, so there is no loss in gain associated with amplifying a cw laser as compared with a pulsed laser. This cw preamplification suppresses the amplified spontaneous emission that would otherwise be present between pulses had the pulse slicing been done before Amplifier #1. Amplifier #2 is two pass. Between the Pockels cells and Amplifier #2, there is a spatial filter to suppress the amplified spontaneous emission further. Behind Amplifier #2, there is another spatial filter to clean the laser-beam spatial profile. Amplifiers #3–#5 are all single pass. In front of Amplifier #3, there is a 7-mm-diameter soft aperture (apodizer) that reshapes the spatial profile of the laser beam from Gaussian to flat top so that the laser pulse can be amplified more efficiently. Behind each of Amplifiers #3–#5, there is an image-relay system that reimages the output aperture of the present stage to the input aperture of the next stage.

The flash lamps fire at 9 Hz. The energies from the flash lamps to the five amplifiers are 17, 36, 70, 70, and 120 J. The pulse burst is shown in Fig. 4. As was mentioned in Ref. 7, because the high pulse repetition rate does not allow the gain medium to be repumped between pulses, the gain seen by each pulse is different because of gain depletion from the previous pulses. The average gains of the five amplifiers, taking losses into account, are 5000, 20, 12, 11, and 7 times, resulting in an overall system gain of approximately 9×10^7. The corresponding energy is approximately 70 mJ for a single 16-ns-duration pulse at 1-MHz repetition rate with 30 pulses per burst. When the repetition rate is adjusted to 500 kHz, the average single-pulse energy is 100 mJ at 1.064 μm.

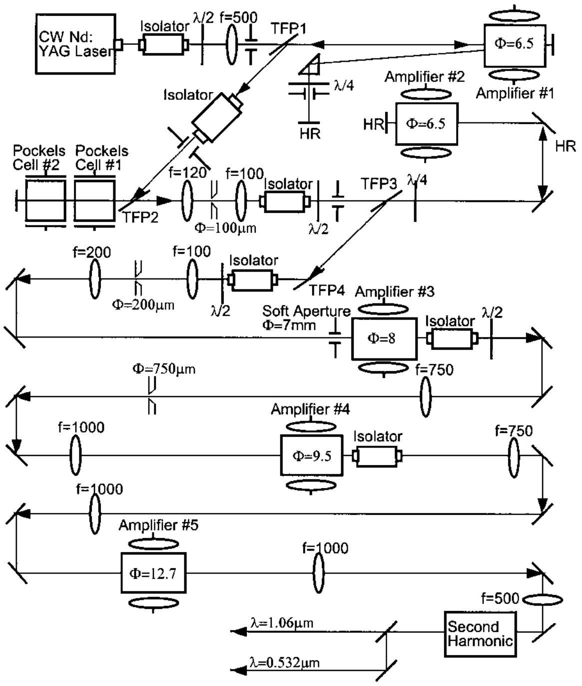

Fig. 3. Schematic diagram of the pulse-burst laser system. $\lambda/2$'s, half-wave plates; TFP1–TFP4, thin-film polarizer; $\lambda/4$'s, quarter-wave plates; HR's, high reflectors.

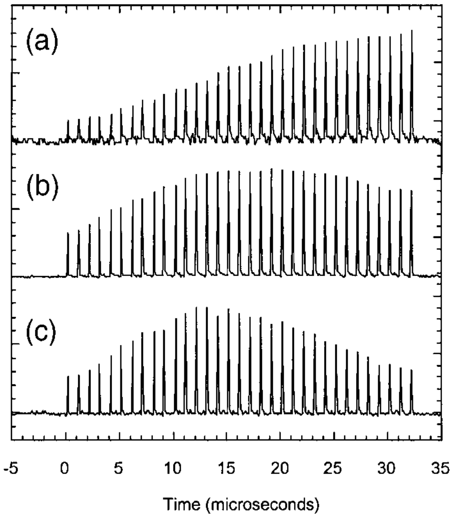

Fig. 4. Oscilloscope trace of pulse burst (a) before and (b) after the final amplifier. (c) Second harmonic. There are 33 pulses in the burst, with an interpulse separation of 1 μs.

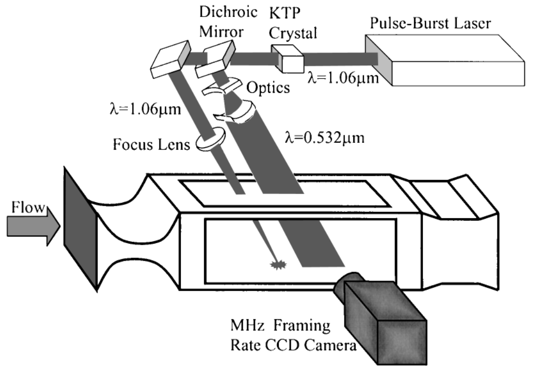

Fig. 5. Experimental setup for studying laser-initiated shock waves and disturbance propagation in a supersonic flow.

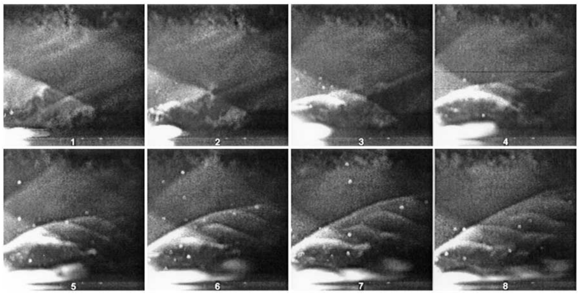

Fig. 6. Eight sequential images showing the propagation of shock waves initiated by a 250-kHz repetition-rate pulse-burst laser. The separation between frames is 4 μs. The Mach 2.5 flow is from left to right. The frame size is 1.27 cm.

The laser-beam diameter to the second-harmonic generator is 6 mm. In the pulse-burst laser system, the energy of each individual pulse is lower than the pulse energy of a conventional single-pulse laser, but the total energy of the whole burst is much higher than that of a conventional laser. Consequently, the doubling crystal should have both a large nonlinear coefficient and a large temperature tolerance. Compared with a KD*P crystal, a KTP crystal has these two advantages. A KTP crystal with a 7 mm × 10 mm cross section is used as the second-harmonic generator. As shown in Fig. 4(c), the variation in pulse energy over the burst is accentuated by the second-harmonic process. The FWHM of the second harmonic is ~14 ns as compared with 16 ns of fundamental, primarily because of the rise time of the fundamental pulse. At 0.5 MHz with 30 pulses per burst, the average single-pulse energy is 25 mJ at 0.532 μm. The reason for the low conversion ratio is the relatively low 1.06-μm input intensity and the high repetition rate.

Coupled with a MHz-framing-rate CCD camera (Princeton Scientific Instruments, Inc., Princeton, N.J.), the pulse-burst laser system has been successfully demonstrated for supersonic-flow visualization. Figure 5 shows the experimental setup used to study a sequence of laser-initiated disturbances and their evolution in a Mach 2.5 wind tunnel. The cross section of the test section in the tunnel is 13 mm × 26 mm. The flow is from left to right. The second-harmonic output of the pulse-burst laser is formed into an approximately 20 mm wide by 100 μm thick sheet. The laser is directed into the flow to generate Rayleigh scattering for visualization. The remaining fundamental beam after the doubling crystal is focused 3 mm upstream from the bottom left-hand corner of the camera frame. The focused 1.06-μm beam generated a breakdown on the inside surface of the wind tunnel. Seeding CO_2 in the flow enhances the Rayleigh scattering.[7]. Figure 6 is a typical sequence of images showing the propagation of disturbance initiated by the pulse-burst laser. The frame rate is 250 kHz, and the frame size is 1.27 cm. At the bottom of each frame is the wall of the tunnel. The bright streak from the bottom left is the radiation from the plasma, which is being swept downstream in the boundary layer. The laser-induced breakdown generated a sequence of disturbances. Because of the supersonic flow, the disturbance could only propagate downstream. Frame 3 shows three disturbances moving on the frame. As more disturbances are generated, they collapse and form an oblique shock. The asymptotic angle of the shock is the Mach angle. This experiment shows that we can control (generate) the disturbances and visualize their propagation in a supersonic flow.

In conclusion, a high-energy MHz-rate pulse-burst laser system has been built. The laser system has been demonstrated as a useful tool for the study of supersonic flow. The pulse-burst concept is well suited for rapid imaging and may be useful in many applications. For example, a frequency-tunable MHz-rate pulsed laser may have an effect on tracking species evolution in combustion and flow diagnostics in the future. Researchers may also use the pulse-burst laser to capture volumetric images by either sweeping the beam or moving the fluid and recording a stack of image planes.

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