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Pulsed Laser Diode for use as a Light Source for Short-Exposure, High-Frame-Rate Flow Visualization

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A pulsed laser diode (PLD) is demonstrated as a practical light source for high-speed digital schlieren and shearing-interferometric cinematogrpahy. Frame rates of greater than 300k fps with exposure times on the order of 10 ns have been achieved with an inexpensive and user-friendly setup. The light source has primarily been used in our laboratory to study nonsteady phenomena in high-speed gas flows. Examples are presented to illustrate the usefulness of the PLD as a light source with characteristics of a narrow band of wavelength, short exposure time, high frame-rate, and long pulse train duration.

I. Introduction

High-speed visualization of density gradients in gas-phase flows using single exposures or multiple frames has been used extensively since the pioneering experiments of Mach (1877). Advances in high-speed camera technology have enabled researchers to capture image series with increasing speed and spatial resolution; light sources have followed this trend of increasing capability. We identify advantageous characteristics for a schlieren light source as: 1) high repetition rate; 2) short exposure time; 3) a long and consistent pulse train; 4) sufficient pulse energy to activate the sensitive camera element; 5) adequate beam quality; 6) low cost.

Researchers have used light emitting diodes (LEDs) and laser diodes as light sources for schlieren setups for some time [1]. Pawliszyn (1986) [2] compares LEDs, laser diodes, and incandescent white light sources for use in imaging density gradients, focusing their efforts on quantifying the "pointing noise." Willert et al. (2012) [3] report schlieren cinematography using a pulsed LED source with repetition rates of up to 1 MHz, pulse durations on the order of 200 ns, and a total acquisition time of about 100 μs. Laurence et al. (2012) [4] report 500 kHz repetition rate schlieren cinematography of fluid-mechanic instability. In that work, the camera is used to gate the light at 500 ns. In Laurence et al. (2014) [5, 6], exposure times on the order of 10 ns are reported with the use of a commercially available laser capable of providing relatively short pulse trains.

At the time of this writing, a non-intensified commercially available continuous framing camera's shortest exposure time is limited to approximately 200 ns. If shorter exposure times are required, a researcher may either use a short pulse-width laser, i.e., a Nd:YAG laser typically used for particle image velocimetry work, or a long duration light source and an intensified camera to gate the light. Haley and Smy (1988) [7] used a pulsed laser diode as "an inexpensive light source for high-speed schlieren photography." In that work, repetition rates of 12k fps with pulse durations of approximately 200 ns are reported.

In this paper, we describe an improvement of that work, increasing the framing rate to greater than 300k fps with pulse durations on the order of 10 ns by using a pulsed laser diode as a light source in high-speed schlieren and shearing interferometry. The light source is small, mobile, inexpensive, and user-friendly.

II. Experimental Setup

Many commercially available laser diodes are suitable for use as light sources for schlieren photography. Two similar laser diodes are used in this work. The first is an Osram SPL PL90_3 pulsed laser diode. It is constructed from three epitaxially stacked emitters with a laser aperture of 200 μm by 10 μm and has a

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peak output power of 75 W, a wavelength of 905 nm, and a maximum pulse width of 100 ns. The rated duty cycle is 0.1%, but this has been exceeded without damage to the diode. It can be purchased at a cost of less than $50. The second is a Sony SLD1332V laser diode. This diode is designed for continuous output at 500 mW but is pulsed with a driver module in the work presented here and has a wavelength of 670 nm. This diode is more expensive than the Osram diode at $690.

Two drivers are used to supply the current to the diode. The PicoLAS LDP-V 03-100 UF3 is used to drive the Sony SLD1332V. The LDP-V 03-100 UF3 driver can deliver up to 3 A of current with a rise time of 1 ns. The PicoLAS LDP-V 50-100 V3 is used to drive the Osram SPL PL90_3. The LDP-V 50-100 V3 driver is capable of delivering up to 50 A output current with a rise time of less than 4 ns at frequencies up to 2 MHz. Both are supplied by a single 15 V, 30 W DC supply. The modules are small, 75 x 44 x 20 mm, and mount easily to an optical table. It is the most expensive component of the light source (≈ $1000).

For some experiments, the output from the diode is collimated by a Thorlabs F810SMA-780, an SMA collimation package with a numerical aperture of 0.25 and a focal length of 36.01 mm, and then transmitted via a Thorlabs M76L01 multimode fiber-optic cable to optical mounting hardware to increase ease of alignment. The cost of the collimator is $212. Fig. 1 shows a photograph of the light source on a standard optical table (1 in spacing) to illustrate the scale.

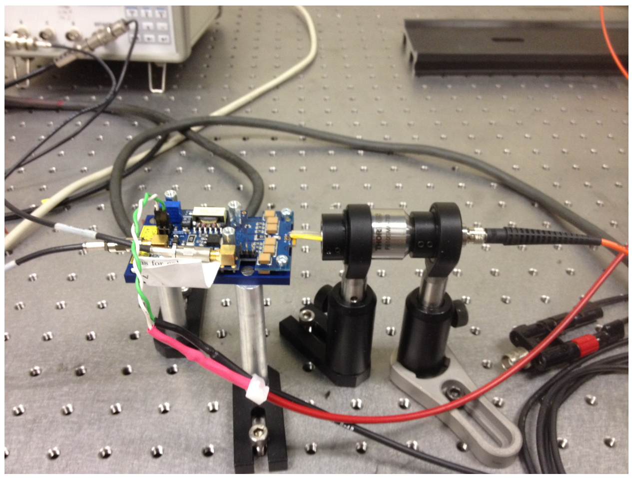


Figure 1: Photograph of the primary components of the light source: the driver module, the collimator, the diode (inside the collimator), and one end of the fiber-optic cable.

The light source is implemented in a standard Z-type schlieren setup, as shown in Fig. 2 (left). The setup can be converted to shearing interferometry by replacing the knife-edge from the schlieren setup with a Wollaston prism and adding linear polarizers. Figure 2 also shows the signal path for the electronic components. The camera, here a Phantom v710 CMOS camera, sends one pulse for each frame to a Berkeley Nucleonics Model 555 pulse delay generator. The delay generator is triggered by the pulse sent from the camera and sends a corresponding pulse of specified width to the driver module after a specified delay time. The delay time must be determined experimentally by changing the delay time until the laser pulse occurs while the camera gate is open. Researchers refer to this operation as camera-mastered operation. Fig. 2 (right) shows the desired timing strategy. The exposure time is determined by the width of the laser pulse instead of the camera shutter, allowing for much shorter exposure times than those achievable with a continuous light source.This operation can be performed in real time by viewing the camera output while operating the laser. This also enables the optics to be aligned in real time, a significant advantage over single-pulse systems.

As pointed out by Willert [3], since the emitter of the laser diode is small, no additional condenser lenses or slits are required to make the diode suitable for a light source in a schlieren setup. A diverging lens is needed to expand the beam to a suitable diameter.

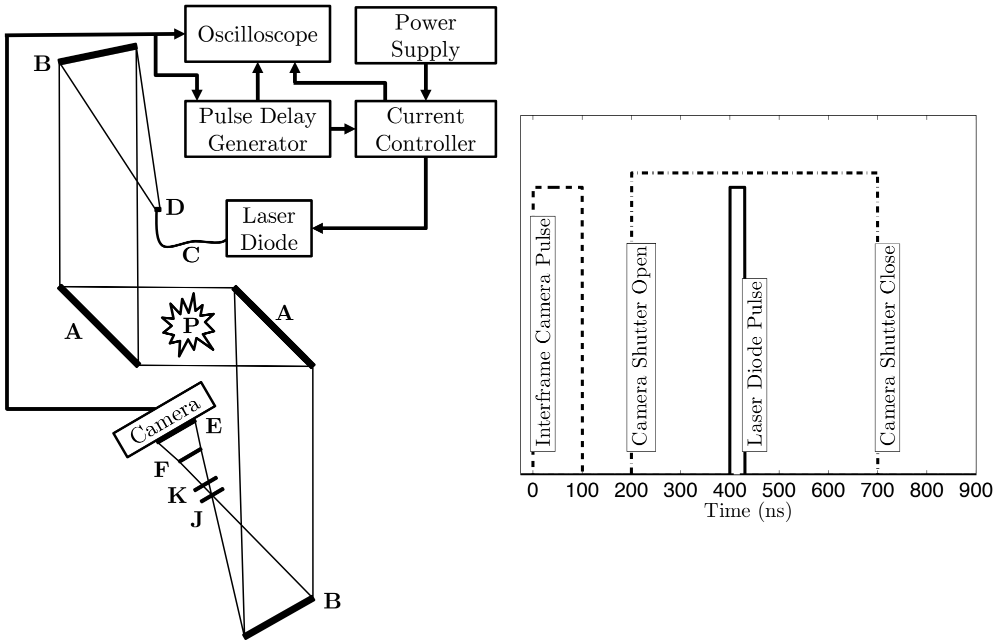


Figure 2: *Left:* Schematic and wiring diagram for the visualization setup and the light source components. A: turning mirror, B: concave mirror ($f = 150$ cm), C: fiber-optic cable, D: fiber-optic cable holder/lens, E: image plane, F: focusing lens ($f = 50.8$ mm), J: schlieren cutoff or Wollaston prism, K: spatial filter or linear polarizer and spatial filter, P: phase object. *Right:* Illustration of the desired timing for triggering the light source. This particular figure is not representative of any specific case, but rather is intended to show the timing of the signals.

The waveform of the pulse output from the LDV-V 50-100 V3 driver and the Osram diode for a pulse widths of approximately 75 ns FWHM (Fig. 3 left) and 200 ns FWHM (Fig. 3 right). Waveforms are measured using a Tektronix TDS2024B digital oscilloscope with an FDS100 photodetector terminated at 50 Ω. The longer pulse time may be of interest to researchers requiring higher light intensity, or if they wish to temporally average over a prescribed time. The output is not a square wave for shorter pulse widths because of the finite rise time of the driver and the FDS100 photodetector which has a rise time, both are on the order of 10 ns. These pulse widths are typical of the light source used in the experiments discussed in the following sections.

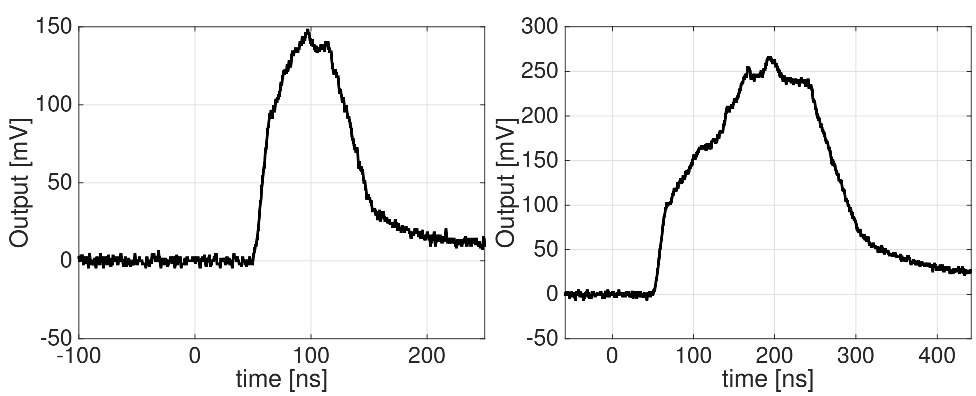


Figure 3: *Left:* Output of the Osram laser diode as measured by a FDS100 photodiode for a 75 ns FWHM pulse. *Right:* Output of the Osram laser diode for a 200 ns FWHM pulse.

III. Supersonic Flow Over a Curved Ramp

The pulsed laser source has been used in a number of experiments in the Caltech Mach 4 Ludwieg Tube. The first experiment analyzed boundary layer transition on a curved ramp of radius 500 mm in Mach 4 flow [8]. Fig. 4 shows two schlieren photographs from that experiment, one taken with a continous white light LED light source (Fig. 4 top) and the other with the pulsed laser source (Fig. 4 bottom). The LED-source image comes from a series of images taken at 3000 fps with an exposure time of 1 ms. The boundary layer is clearly visible in the image, but the exposure time is too long to resolve transient vortical structures indicative of turbulence. The image taken with the pulsed source is from a series taken at 6000 fps with a pulse width of 80 ns. Turbulent structures in the boundary layer are clearly visible in this image, which allows for a clear transition location measurement to be made. Individual compression waves above the surface of the ramp also become distinguishable. It should be noted that the images (as with all results presented heretofore) are part of a long "movie." The movie length is limited, not by the diode/driver combination, but by the on-board memory of the camera. In Fig. 4, this is approximately 400 ms.

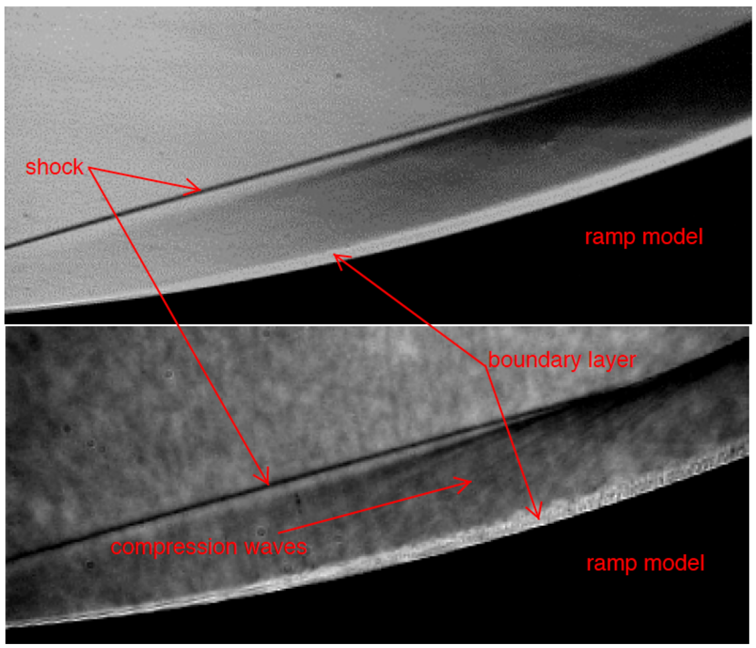


Figure 4: Schlieren images using the continous LED source (top) and the pulsed laser source (bottom) of a curved ramp in Mach 4 flow.

IV. Gas Injection in Supersonic Flow

The second set of experiments analyzes the effects of gas injection into the boundary layer on a cone [9]. Figure 5 shows an image taken with a white light LED at 3000 fps with an exposure time of 30 μs. Weak conical shock waves are visible in this image as is the injection layer formed downstream of the porous injector section on the cone, marked by red lines in the image. A series of images taken at 100k fps with a pulse width of 40 ns was taken of the region near the injector to investigate the instability in the injection layer. One such image is shown in Fig. 6. Coherent structures in the injection layer are clearly visible and their evolution in time can be readily observed by viewing the images as a movie. The images are of sufficient quality to statistically determine the spatial wavelengths of the structures using an image-processing algorithm [10].

The diode is used at 40 times its rated duty cycle (0.1%) in this experiment with no clear damage. The upper limit of the duty cycle for the Osram diode has not been determined.

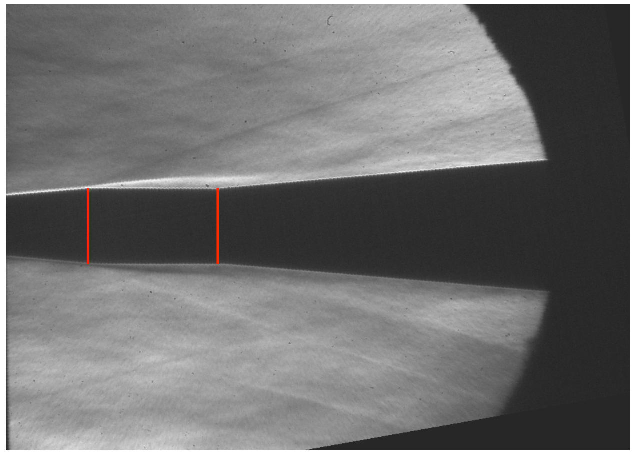


Figure 5: Schlieren image of a cone with boundary layer injection in Mach 4 flow with a continous white light LED source with an exposure time of 30 μs.

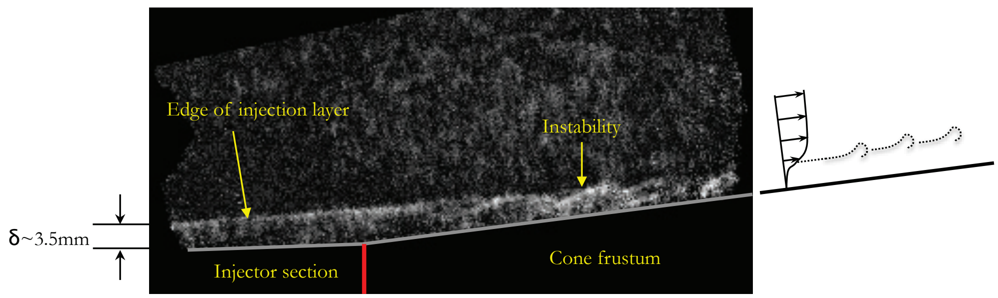
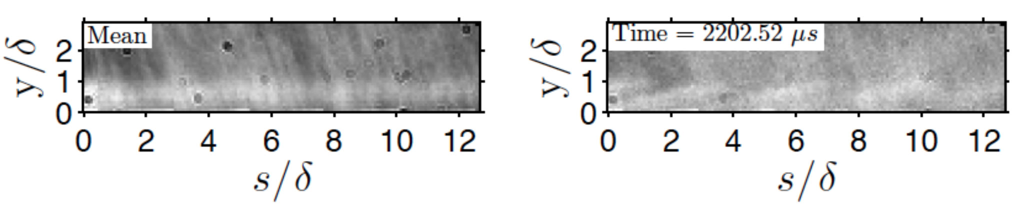


Figure 6: Schlieren image of the injector section of the cone in Figure 5 taken with the pulsed laser source with a pulse width of 40 ns. The instability is illustrated on the right-hand side of the figure.

V. Hypervelocity Boundary Layer Instability

The Sony diode was used to image instability waves in a hypervelocity boundary layer [11]. The experiments were performed in the T5 hypervelocity shock tunnel at Caltech using a 5 degree half-angle cone as the model. Fig. 7 shows the result from an experiment using air as the test gas with a boundary layer edge velocity of 3464 m/s and a boundary layer thickness of 1-2 mm. The most amplified unstable frequency in this boundary layer is calculated to be approximately 600 kHz. The diode is pulsed at 320k frames per second with a 12 ns pulse width (duty cycle 0.38%). The field of view is approximately 780 mm from the tip of the cone and is 192x56 pixels. The low spatial resolution allows for a higher frame rate than that used in Sec. IV. Fig. 7a is a mean of 10 individual images that simulates using a longer exposure than Fig. 7b, which is a single image. Instability waves can be clearly identified in Fig. 7b.

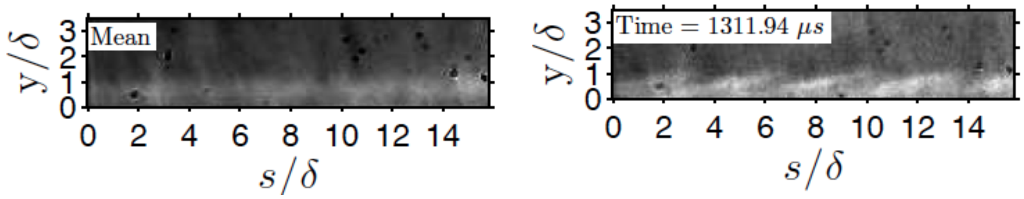


(a) Mean of 10 images

(b) Single image

Figure 7: Images of a hypervelocity boundary layer in air. Flow is from left to right.

Fig. 8 shows a similar result for hypervelocity flow in nitrogen. Here the boundary layer edge velocity is 3859 m/s, the boundary layer thickness is 2-2.5 mm and the most amplified unstable frequency is again approximately 600 kHz. The field of view is in the same position on the cone as in Fig. 7 except the spatial resolution is increased to 256x128 pixels. The frame rate is correspondingly reduced to 150k frames per second but the pulse width remains at 12 ns (duty cycle 0.18%). Instability waves are again clearly visible in Fig. 8b.



(a) Mean of 10 images

(b) Single image

Figure 8: Images of a hypervelocity boundary layer in nitrogen. Flow is from left to right.

VI. Planar detonation waves

The Sony diode was also used to image planar detonation waves in the GALCIT Detonation Tube (GDT) [12] as part of a study to examine planar detonation reflection. Figure 9 shows an example image from these experiments. An LDP-V 03-100 UF3 driver was used to produce this image instead of the LDP-V 50-100 V3 driver used in the other experiments presented in this work. The drivers are quite similar but the LDP-V 03-100 UF3 operates at lower current output (3 A maximum versus 50 A maximum), has a shorter rise time (800 ps versus 2.3 ns), a shorter minimum pulse width (1 ns versus 12 ns), and a higher maximum pulse rate (35 MHz versus 2 MHz). Shown in figure 9 is a schlieren image of a gaseous detonation propagating to the right through stoichiometric hydrogen-oxygen at initial pressure 15 kPa. The schlieren depth of focus and GDT experimental setup resulted in an optical integration length of 150 mm which causes the detonation cellular structure (such as visualized in [13]) to not be clearly depicted and instead results in the multitude of waves observed in figure 9. The detonation wave speed was 2.8 km/s and the field of view was approximately 10 mm wide. The combination of a fast wave with a small field of view implies that a short laser pulse time is needed; this image was taken with a 10 ns laser pulse. The illumination produced by the detonation wave necessitated the use of a laser line filter matching the light emitted from the diode to filter the self-illumination resulting from the combustion.

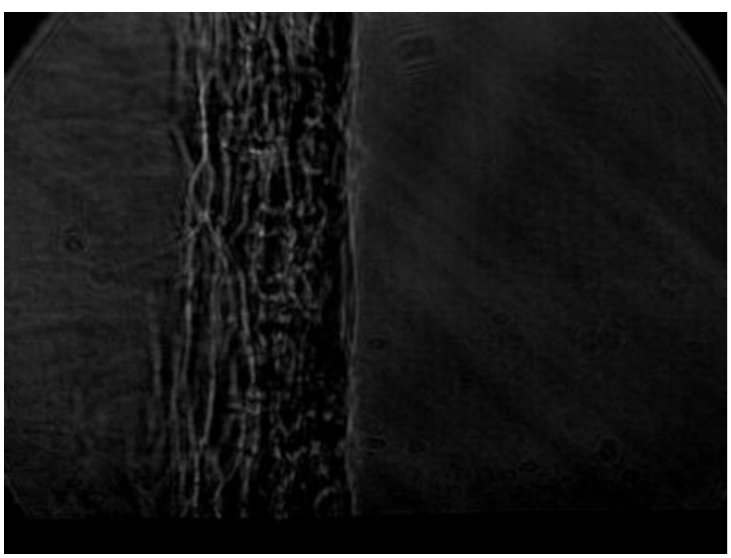


Figure 9: Image of a detonation wave propagating into a stoichiometric hydrogen-oxygen mixture. Wave propagation is from left to right.

VII. Other Applications

Other gas dynamics phenomena have been documented to demonstrate the capabilities of the light source. Fig. 10 shows the propagation of a weak shock wave into partial vacuum in the test section of the Caltech Ludwieg Tube during the startup process of the tunnel with a diaphragm upstream of the nozzle. The images are taken at 100k fps with a pulse width of 40 ns. The shock speed is measured to be approximately 700 m/s from the series of images. This shock is not visible due to blurring if the shutter of the camera is used to gate the light, as exposure time is limited to about 1 μs.

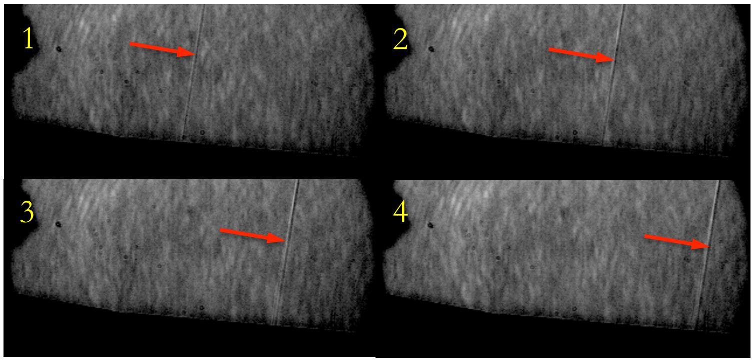


Figure 10: A schlieren image showing shock propagation in the Caltech Mach 4 Ludwieg tube during tunnel startup at 100k fps with a pulse width of 40 ns. The red arrows indicate the shock location.

Fig. 11 (left) shows a hot soldering iron imaged using shearing interferometry at infinite fringe instead of a schlieren image. Fringes are clearly visible near the hot tip of the iron. The pulse width for this image is 30 ns (Fig. 11 (right)).

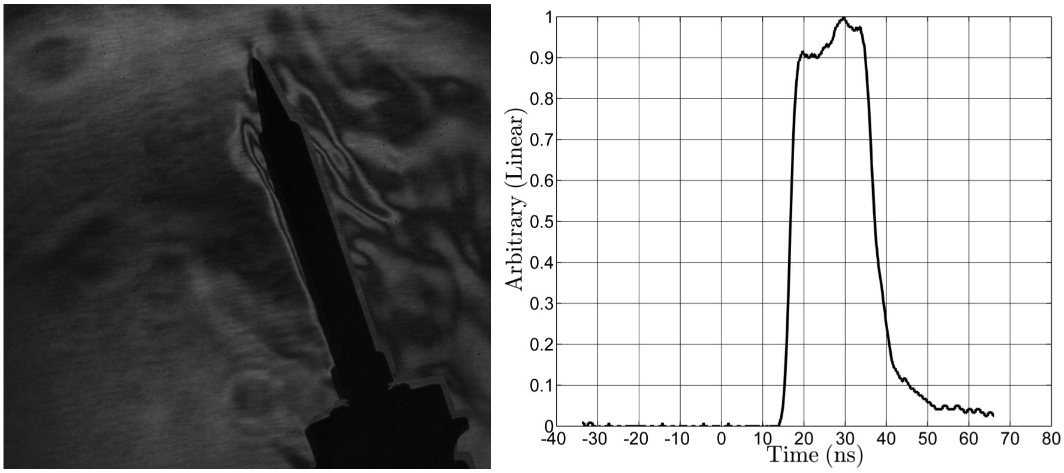


Figure 11: *Left:* A shearing interferometry image of a soldering iron at infinite fringe taken with the pulsed laser source with a pulse width of ≈ 25 ns. *Right:* Time-intensity profile of the laser pulse light source.

VIII. Conclusion

The pulsed laser source presented in this paper has significant advantages in performance and cost compared to other commonly used light sources. The highest frame rate achieved was in excess of 300k fps with a pulse width of 12 ns. A continuous chain of pulses at this rate and width can be produced. The components for the light source can be purchased for under $2000, and the source is readily interchangeable with traditional continuous light sources in optical setups due to its small size, low power requirements, and ease of alignment. The pulsed laser source is demonstrated to be a useful tool in visualizing high-speed and transient phenomena in gas dynamics.

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