Development and characterization of an inexpensive LED-based light source for high-frame-rate schlieren imaging

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This work presents characterization results of a 623 nm light emitting diode (LED) based light source developed for low-cost, high frame rate schlieren imaging. The LED was overdriven up to 20 times the rated current while generating 100 ns pulses at a 1 MHz repetition rate. Circuit response, pulse train characteristics, and temperature effects were observed over a large range of input voltages. Relative brightness data was measured with a photodiode and further examined within a schlieren system. Flow visualization of a decaying Mach 3 shock wave were obtained with the system. The wave was produced in a shock tube facility used for aerodynamic measurements. The effect of the light source on image quality, including motion blur are analyzed. Furthermore, shock velocity measurements obtained from the schlieren images are reported.

I. Introduction

Schlieren imaging is a conventional, non-intrusive method for visualizing density gradients in transparent media. With advancements in high speed photography, it has become a cost-effective method for imaging high-speed, transient events in fluid mechanics. In an experiment by Austin et al. (2005), a schlieren system using a pulsed Q-ruby laser and model 189 Whitley framing camera imaged reaction zones in unstable detonations with velocities up to 2000 m/s.[1] In another study by Smart and Trexler (2004), single shot schlieren images of the starting process in a Mach 4 inlet were acquired.[2] Additionally, schlieren imaging used by Johansen and Ciccarelli (2009) with a Xenon arc lamp and 1024 PCI high speed digital camera imaged unburned gas ahead of detonations.[3]

When imaging events with short time scales, temporal characteristics of the imaging equipment become important. While analyzing single-shot schlieren light characteristics, Krehl *et al.* (1995) ranked brightness and short pulse durations as the most important.[4] Bright light sources reduce the minimum discernible contrast while short pulse durations reduce image blur.[5] With continuous light sources, such as high intensity discharge (HID) lamps, exposure times are completely limited by camera shutter settings. Since HIDs are inexpensive, easy to use, and are capable of producing bright light, they are common light sources for schlieren applications.[6–9]

Pulsed operation of light sources such as lasers and light emitting diodes (LEDs) can reduce the effective exposure time for a given frame rate. While lasers are capable of bright, femtosecond pulse durations, they are typically expensive. Another disadvantage of lasers is that coherent light sources, when used with conventional cutoffs such as knife edges, introduce diffraction patterns into schlieren images.[5] Despite this, examples of pulsed lasers for schlieren use can be found in the literature.[10–12] Recent work has focused on pulsed LED development for high-speed schlieren applications. Buttsworth (2003) developed a pulsed LED for schlieren imaging capable of 1.5 μs pulse durations and successfully imaged a vertical hot air jet.[13] Pulsed LED technology was further refined by Willert *et al.* (2012), who developed and evaluated an overdriven LED system capable of sub microsecond pulse durations.[14] The performance of the LED system was assessed based on pulse brightness, consistency, and response times. More recently, Wilson *et al.* (2014)

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made quantitative and qualitative comparisons between an overdriven LED and a high intensity discharge (HID) lamp.[15] Both light sources were used in a z-type schlieren setup to image a shock wave from an under expanded jet and compared based on signal to noise ratio (SNR). It was found that the LED outperformed the HID when imaging high speed events such as shock waves.

To the authors' knowledge, pulse durations of LED-based light source setups have not been reduced below 300 ns with frequencies in the MHz range. In this work, characterization results of an optimized, overdriven LED system capable of 100 ns pulses in the MHz range are presented. Additionally, schlieren images of a decaying cylindrical shock wave (Mach 3) are obtained with the LED system. This system is synchronized with the propagating shock using a piezoelectric pressure sensor. Decaying cylindrical shock front propagation is imaged for blast wave mitigation techniques.

II. LED Design Modifications

The LED design developed for this study is a revision of one presented by Wilson *et al.* (2014).[15] One of the main modifications was the replacement of two 680 μF capacitors with a single 22 mF capacitor. The motivation for this change was to improve the duration of constant light output over long pulse trains (>100). Another change was to choose an LED best matched to the camera system. The Photron FASTCAM SA5 is most sensitive to wavelengths of 639 nm. Additionally, the red CBT-120 LED has a higher radiometric flux than the green. Therefore, the Luminus LED with a dominant wavelength of 623 nm was selected. Note that the total cost of the LED and other components at the time of this writing is approximately $160 USD.

Heat transfer calculations using conservation of energy and the lumped capacitance method suggested a junction temperature increase of 19 K over 100 pulses with 100 ns durations at 100 kHz and 600 A. While this increase is within safe limits, a 225 mm^2 CP85138 peltier cooler (CUI) and CPU heat sink were attached to the LED. At higher pulse frequencies approaching 1 MHz, the junction temperature is expected to exceed 398 K, necessitating cooling.

III. Experimental Setup

Light output evaluation of the pulsed LED was conducted in a single pass, z-type schlieren system with a Photron FASTCAM SA5 high speed camera collecting light. Light from the LED was passed through a condenser lens before reflecting off a 20.32 cm diameter parabolic mirror. Collimated light was then directed through the test section before reflecting off a second parabolic mirror. After being partially blocked by a knife edge, light was collected by a FASTCAM SA5 high speed camera (Photron) with a 300 mm lens (NIKKOR). The first and second mirrors were placed one focal length (3.05 m) from the light source and knife edge, respectively. During these experiments, the cutoff was positioned such that it blocked 50% of the LED emitting area, ensuring consistency throughout imaging. Figure (1) shows a schematic of the setup.

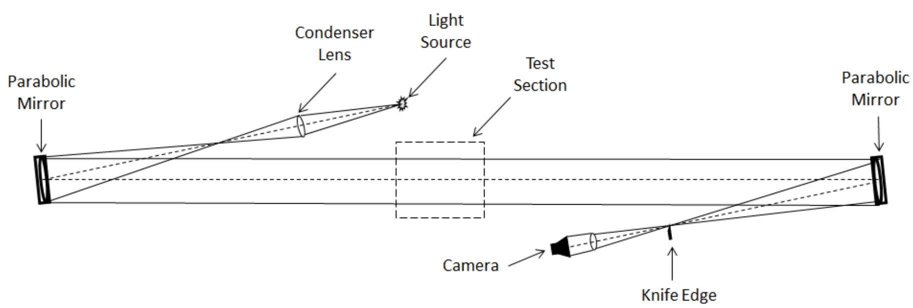

Figure 1. Top down view of a z-type schlieren setup

Shock waves were generated in a 6061-T6 aluminum shock tube with internal cross-section dimensions of 15.24×2.54 cm (test section in figure (1)). A mild steel shim stock diaphragm with a 0.10 mm thickness was located 76.2 cm from the viewing section. Acrylic windows allowed schlieren imaging of the shock wave.

Figure (2) shows the shock chamber used for the experiments. Initially, the driven section was set to 6.89 kPa of air; the driver side filled with helium up to a pressure of 2.76 MPa. The driver and driven pressures were monitored with PX409-500A5V and PX409-015A5V pressure transducers (Omega), respectively. In order to generate a cylindrical shock front, a 6.35 mm slit was placed 8.57 cm upstream of the viewing section. The planar shock wave, initially generated by the diaphragm burst, diffracted through the slit and formed a cylindrical shock front.

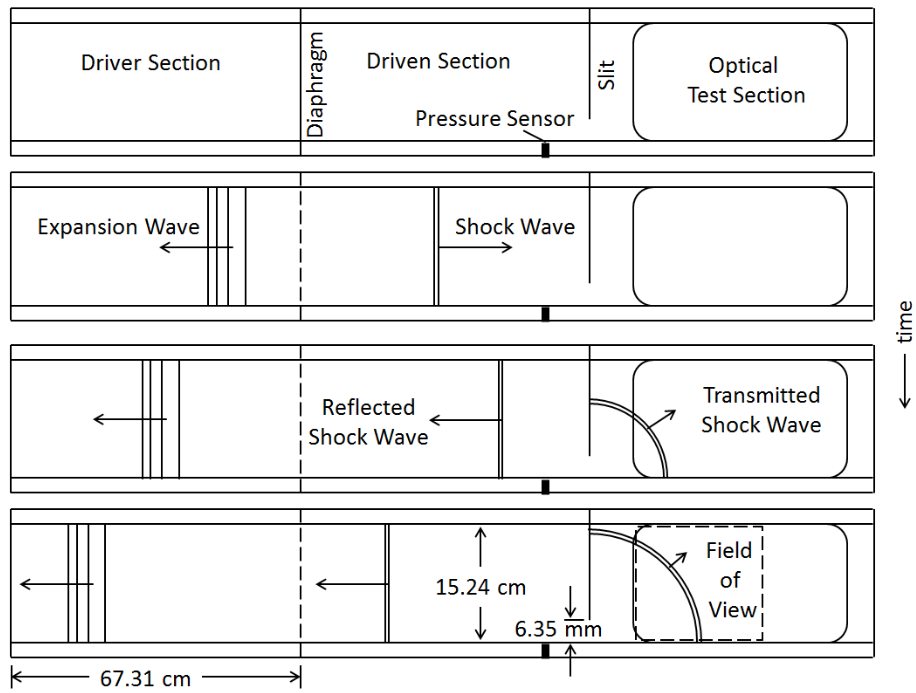

Figure 2. Shock chamber used in the experiment

The camera and LED were triggered with a 113B26 piezoelectric pressure transducer (PCB) located 39.05 cm from the slit. The rising edge associated with the planar shock wave triggered the 6366 x-series DAQ (National Instruments) to produce a pulse train of 500 pulses with 100 ns durations at 25 kHz. This pulse train was sent to the camera and LED, simultaneously. Captured images were post processed in MATLAB.

IV. Results

A. Light Source Characterization

The LED was driven by a custom-made pulser circuit. A detailed schematic can be found in the work by Wilson *et al.* (2014).[15] In order to characterize the circuit, the LED was placed 2 mm from a DET02AFC photodiode (Thorlabs) and triggered with an NI myDAQ (National Instruments) data acquisition system. During operation,voltage is supplied to the capacitor and MOSFET driver. The input trigger, current draw, and photodiode output waveforms were captured on an MSO-X 3024A oscilloscope (Agilent).

A primary goal of circuit characterization was determining the voltage-current relationship. As V_{SUPPLY} and V_{GATE} were varied, current draw and LED output traces were captured on the oscilloscope. Note that current draw was measured as a voltage drop across a 5 mΩ resistor installed on the pulser circuit. It was found that while there is a linear dependence of current on input voltages, V_{GATE} limits the maximum current draw through the pulser circuit; once V_{GATE} reached 12 V, there was no observed increase in current draw for increases in V_{SUPPLY}. The authors suspect that this results from relative resistances between the circuit and MOSFET transistor. While the MOSFET resistance decreases with increasing V_{GATE}, when V_{GATE} = 12 V, circuit resistance including contacts, printed circuit board traces, and the circuit sense resistor dominates. Thereafter, current draw is more strongly affected by V_{SUPPLY} than V_{GATE}.

Figure (3) shows an oscilloscope trace of the circuit response to a 5 V, 100 ns input trigger. It is important to note a 67 ns delay between the start of the input trigger and LED pulse. This was observed over all input voltages. In the study by Wilson *et al.* this delay was 125 ns and was attributed to MOSFET latency.[15] According to the device datasheet, the current MOSFET has a latency range from 60-90 ns. Also important

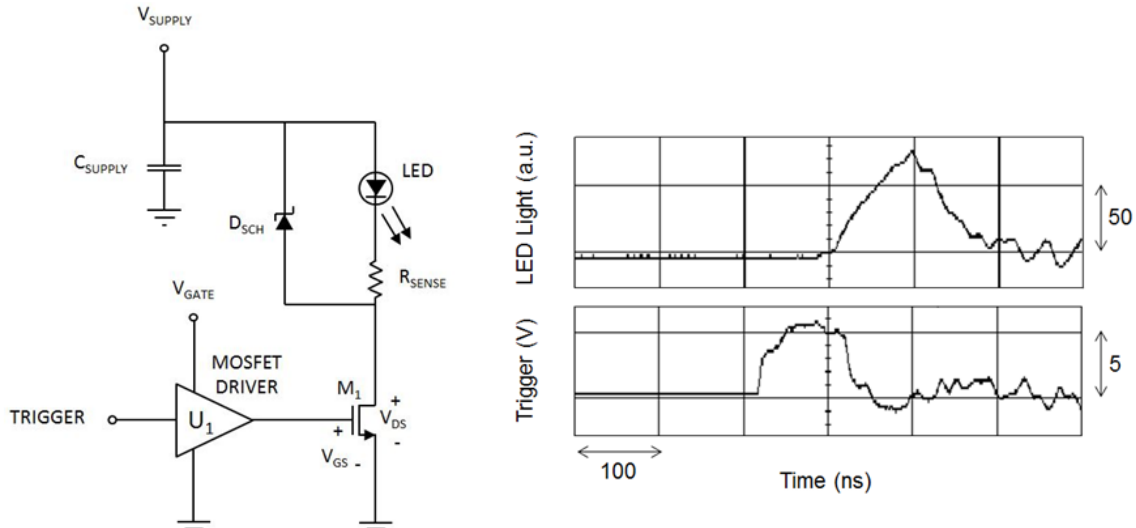

Figure 3. Circuit schematic (left) and response to a 5V, 100 ns trigger with V_{SUPPLY} = 10 V and V_{GATE} = 28 V (right)

to note is that while the trigger is approximately a square wave, the LED output is a rising followed by a falling exponential, indication the LED is not reaching peak output. Full width at half maximum pulse output was measured to be 101.56 ns. When capturing schlieren images, the LED operates in a burst mode synchronized with the camera. No adverse effects on LED performance were observed over 50 pulse trains of 100 pulses with the LED operating at 100 kHz with 100 ns pulses and a current loading of 600 A.

Frame averaged pulses measured by MATLAB for a pulse train of 500 pulses with 100 ns durations at a pulse frequency of 1 MHz are shown in figure (4). For camera frame rates of 1 MHz, the resolution was 64×16. Note that over all frequencies, the first LED pulse is consistently dimmer than subsequent pulses. This is due to the semiconductor nature of the LED; increased temperatures reduce LED resistance, increasing current draw (and therefore light output) for constant supply voltages. Once temperature effects stabilize, consistent light output is maintained. Interestingly, despite the high pulse frequency and system current draw, there is minimal light decay (3.38%). Because it is expected that light decay is proportional to the voltage decay of the discharging capacitor, it is expected that the LED-based light source can operate at higher frequencies.

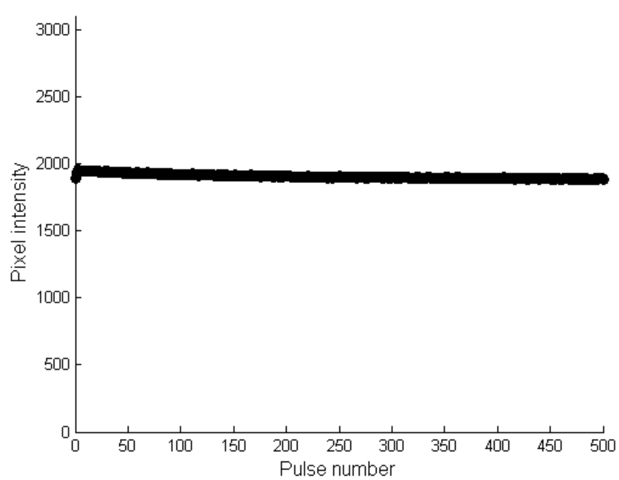

Figure 4. Pixel intensities over a pulse train of 500 pulses with 100 ns durations at 1 MHz

Temperature effects were also examined. Measurements at constant V_m and V_c were recorded in order to quantify the effects of cooling on current draw. As the LED cooled, junction temperature (T_j) was monitored via an NCP15XH103J03RC thermistor (Murata) attached to the LED. Curiously, over a temperature difference of 36 K, there was no observable change in current draw. Equation (1), the ideal diode law, describes the effects of temperature and voltage on diode current draw. I is the net current flowing through diode, I_0 is the reverse saturation current, q is the absolute value of an electron charge, V is the voltage across the diode, k is Boltzmann's constant, and T is absolute temperature. From equation (1), as temperature decreases, higher currents are achieved for constant voltages. But, I_0 increases with temperature and that effect is stronger. So, current draw increases with temperature. The authors believe that the discrepancy between the behavior predicted by Equation (1) and observations results from competing resistances in the circuit, negating the effects of Equation (1).

$$I = I_0(e^{\frac{qV}{kT}} - 1) \tag{1}$$

B. Schlieren Assessment

Figure (5) shows a series of schlieren images captured at 25000 fps. Note that images are shown in 40 μs time steps. Because the shock wave is the largest density gradient, it is the most distinct. As can be seen, there is negligible image blur. With a magnification of approximately 0.59 mm/pixel and an average radial shock speed of 1080 m/s (Mach 3.1), motion blur with the pulsed LED is estimated to be 0.18 pixels. Using the camera's minimum exposure (1 μs) to freeze the flow with a continuous light source would result in a pixel blur of 1.8 pixels.

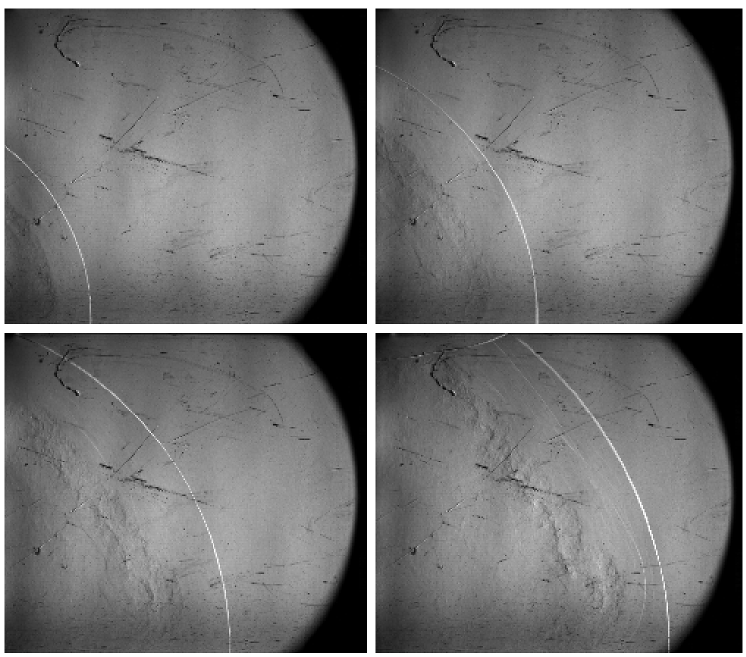

Figure 5. Successive images of a Mach 3 cylindrical shock wave propagation captured at 25000 fps

Once the diaphragm breaks, a series of compression waves coalesce to form a shock front. With a diaphragm pressure ratio of 400, and helium driving air, one dimensional theory predicts a shock Mach number of 4.68 (1605 m/s). After diffracting through the slit, however, the radial Mach number is reduced to approximately Mach 3. Figure (6) shows the measured schlieren radial velocities as a function of angle from the horizontal plane. Because the shock wave does not start from a point source, like a conventional blast wave, it is expected that velocity would depend on radius from the slit, angle, and time.

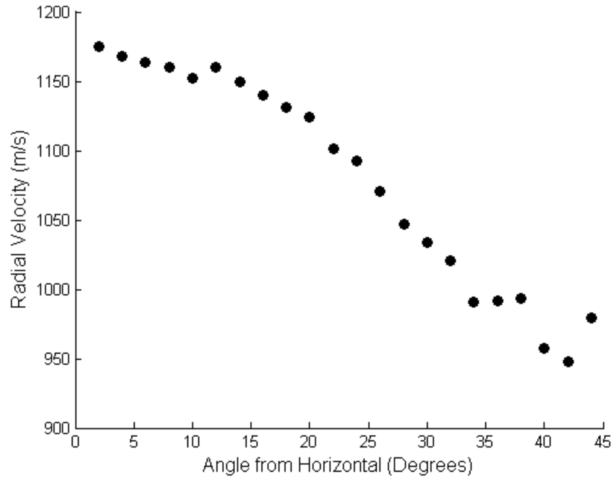

Figure 6. Radial velocity profile of a diffracted shock imaged at 100000 fps

V. Conclusions

An overdriven LED, modified from previous work was characterized with the intention of using it for high speed schlieren imaging. Current, pixel intensity, and temperature measurements were made to further define operating conditions. It was found that the LED setup is capable of sustained brightness at current loadings up to and including 600 A for pulse trains of 500 pulses with 100 ns durations up to and including 1 MHz. Additionally, it was found that temperature has negligible effects on system performance at operating conditions. Schlieren images and radial velocity profiles of a Mach 3, decaying cylindrical shock wave were acquired using a z-type schlieren system, demonstrating the effectiveness of the LED setup for high-frame-rate schlieren imaging. A clear advantage over continuous light sources that rely on camera exposure settings to freeze the flow is demonstrated.

Acknowledgments

Daniel Lincoln would like to thank Garrett Gustafson for his help during the initial stages of circuit building and characterization. Financial support for this project was provided by Alberta Innovates Technology Futures (AITF) and the CMC Microsystems Embedded Systems Canada (emSYSCAN) program.

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