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Pulsed Operation of High Power Light Emitting Diodes for Flow Velocimetry

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ABSTRACT

High powered light emitting diodes (LED) are investigated for possible uses as light sources in flow diagnostics, in particular, as an alternative to laser-based illumination in particle imaging flow velocimetry. Recent developments in solid state illumination resulted in mass-produced LEDs that provide average radiant power in excess of 10 Watt. By operating these LEDs with short duration, pulsed currents that are considerably beyond their continuous current damage threshold, light pulses can be generated that are sufficient to the illuminate and image micron sized particles in flow velocimetry. kilohertz frame rate PIV measurements in water are presented. The feasibility of LED-based PIV measurements in air is also demonstrated.

LIST OF SYMOBLS

A_{lum}	emitter luminescent area
N.A.	numerical aperture
$I_{\mathrm{f,cw}}$	nominal continuous forward current
$I_{\mathrm{f,max}}$	maximum continuous forward current
λ_{o}	dominant emission wavelength
Φ_v	luminous flux in lumen (lm)
Φ_r	radiometric flux in Watt (W)
τ	pulse delay

1. INTRODUCTION

While earlier generations of LEDs were primarily used as indicators in every-day electronics, recent developments have resulted in mass-produced devices whose light output rivals that of conventional light sources such as incandescent light bulbs and now find an increased range of applications ranging from architectural lighting to projection system and automotive head lights. In the framework of flow diagnostics LEDs promise a number of attractive advantages in comparison to lasers and therefore deserve closer investigation. Aside from the dramatically reduced cost of procurement and considerably longer life time, a LED provides incoherent light over a rather wide wavelength range (typ. $\pm 10-30\,$nm) which alleviates many issues related to speckle artifacts found in laser based illumination. If operated in pulsed mode, the luminosity signal of a LED is extremely stable, both in terms of intensity as well as spatial intensity distribution.

Another interesting characteristic and a main point of emphasis of the present work, is that LEDs can be operated significantly beyond their damage threshold using high current, short duration pulses. In this case, the temperature within the substrate (junction temperature) stays below the damage threshold while the photon generation per time-unit is approximately increased in proportion to the current increase [1, 2]. This makes the LED particular interesting for utilization as a pulsed light source in image based diagnostics. The literature reports the use of LEDs in Schlieren imaging [3], bubble shadowgraphy [4, 5, 6], shadow velocimetry [7], PIV [8] as well as micro-PIV [9]. If operated in a forward scatter shadowgraphy arrangement short duration pulses below 250 ns enable high-speed shadowgraphy in the 100 kHz range of kerosene sprays at high magnification [10]. The present work focusses on side-scatter illumination geometries commonly used in PIV and PTV which requires significantly higher illumination intensities.

2. OVERVIEW OF HIGH CURRENT LEDS

Table 1 lists the characteristics of several representative LEDs tested in the course of the feasibility study. Mainly green LEDs were investigated, in part, because present day imaging sensors exhibit peak quantum efficiencies in the yellow/green range ($550-530\,$nm), similar to the response of the human eye. The listed devices represent two different types of LEDs: The first three, available from Philips Lumileds, are designed for general illumination purposes and contain rather small luminous emission chips which are encapsulated in a lens shaped clear dome. The other two devices, available from Luminus Devices Inc., are specifically designed for projection systems. Here the luminescent substrate is covered by a thin glass window similar to an imaging sensor. Contrary to most commonly available LEDs these devices are essentially surface emitters with a nearly constant intensity distribution per unit area. This is achieved by a photonic lattice bonded to the surface of the emitter which channels the light through micron-sized, surface-normal holes. Because of this, the radiation pattern is more bundled than for conventional high-current LEDs.

Emitter	$I_{\mathrm{f,cw}}$ (A)	Φ_V (lm)	λ_{o} (nm)	$I_{\mathrm{f,max}}$ (A)	A_{lum} (mm^2)
LXHL-PD09	1.4	140	627	1.54	$\approx 1.5\times 1.5$
LXHL-PL09	1.4	110	590	1.54	$\approx 1.5\times 1.5$
LXHL-PM02	0.7	160	530	1.00	$\approx 2\times 2$
CBT40	5.9	625	528	12	2.09×1.87
CBT120	18	2100	528	36	4.6×2.6

Table 1: Specifications of selected high-current LEDs

3. LED CHARACTERISTICS IN PULSED OPERATION

Figure 1 illustrates the increased luminosity of two high power LEDs that are driven with short-duration current pulses (here $1\,\mu$s at 1 kHz). In both cases the LEDs are driven up to maximum currents in the 30 A range which is more than a factor 20 higher than the rated current I_f for red LED. For the green LED the rated current is exceeded by a factor of 5 suggesting further increase without damage to the device. In fact none of the tested devices suffered any noticeable damage when operated in pulsed mode at these current levels and low

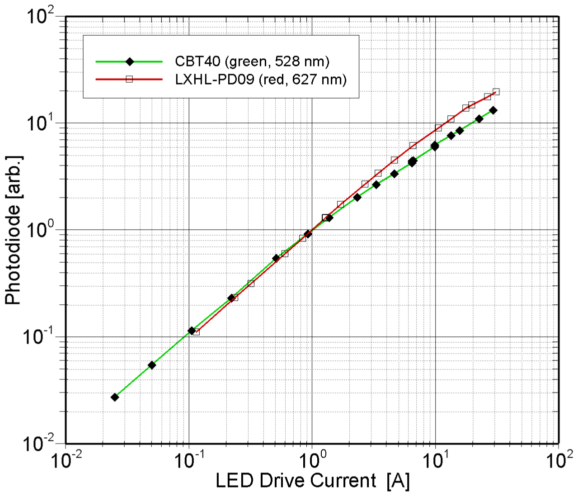

Figure 1: Luminosity of high power LEDs driven with $1\mu s$ current pulses

duty cycle (less than 1 : 100).

The data shown in figure 1 confirms the known increase of luminous flux Φ_v with an increasing drive current I_f. For the red LED the increase of current leads to a proportional increase for low drive currents. At higher currents the efficiency factor or proportionality reduces to about 0.4. The green LED (CBT-40) exhibits a similar behavior for low currents but decreases to about 0.35 at currents beyond 10 A. This indicates a decreasing proportionality with increasing drive currents due to saturation effects. Not shown is data for the 5W green LED (LXHL-PM02) for which the proportionality decreases to 20% at currents beyond 30 A. In comparison the high power device CBT-120, which has a 3 times larger luminescent area than the CBT-40, exhibits an proportionality of 40% at 40 A, indicating considerable margins for operation at even higher currents.

Measurements of the type shown in figure 1 allow an approximate extrapolation of luminous flux (or effective pulse energy) at even higher currents. The smaller high current devices LXHL-PD09 (red) and LXHL-PM02 (green) could be driven at pulsed currents of 50 A without immediate damage, exceeding the rated current by a factor of 30 and 70, respectively. This suggests that the stronger devices CBT-40 and CBT-120 can be driven at significantly higher currents in the $100-200$ A range. The data sheet for the CBT-120 quotes a radiometric flux $\Phi_r = 6.3$ W ($\Phi_v = 3100$ lm) when driven at a pulsed current of $I_f = 30$ A at 240 Hz and a 50% duty cycle [11]. The effective pulse power then is $\Phi_r = 12.6$ W for the duration of the current pulse. Assuming a conservative proportionality of 35% light output increase with respect to increasing current – as indicated in figure 1 – this would result in an effective pulse power of close 60 W at $I_f = 200$ A drive current. This corresponds to a pulse energy of $60\mu J$ for a $1\mu s$ pulse. As will be shown later this is sufficient to perform reliable high-speed PIV measurements in water.

A side effect of the pulsed operation of LEDs is that the emission wavelength may shift considerably as the current is increased. This effect is shown in figure 2 for two LED emitters. The drive pulses are approximately chosen to be of similar integral input power to maintain an average junction temperature. While the amber LED (LXHL-PL09) shows only a minor frequency shift of about $\Delta\lambda = 2$ nm toward longer wavelengths, the green device shifts by more than $\Delta\lambda =$ 30 nm toward a cyan color. The effect is characteristic for the respective junction materials that the devices are made of: typically GaAsP or AlInGaP for the red and orange luminescence and InGaN for the green and blue LEDs [12]. The spectral width increases slightly for both devices as the drive current increases. In general green device has a much wider emission spectrum which is also attributed to the junction material (so called *alloy broadening* [12]). While the frequency shift may not be a issue for many velocimetry applications it nonetheless may be of interest when color-selective cameras and filters are used.

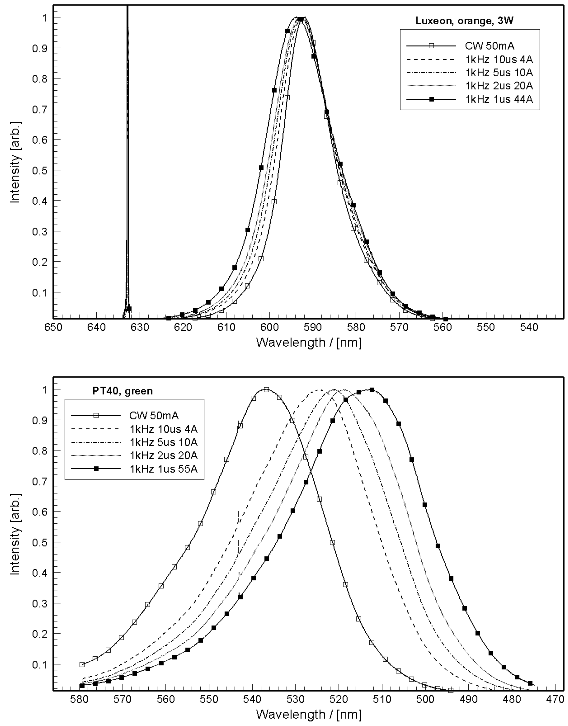

Figure 2: Spectral intensity distribution of LEDs operating in continuous and pulse modes. Top: LXHL-PL09 (amber); bottom: CBT-40 (green)

While none of the devices were damaged due to current over-driving, increased aging will occur resulting in a gradual reduction of light emission, but this has not been investigated by the authors. Driving the LEDs at high currents briefly increases the junction temperature which strains the crystal causing defects in its lattice which then no longer contribute to light generation.

4. PIV USING LED

As mentioned in the introduction, the literature reports a number of earlier PIV applications involving LED clusters as light sources [4, 8, 7, 9, 5]. In these applications the LEDs were rarely overdriven to levels reported here and generally operated in a in-line imaging arrangement or relied on large particles to achieve sufficient light scattering.

The present LED-PIV investigations focussed on using single LEDs to illuminate particles in side-scatter which is commonly used in planar PIV. Initially volume illumination was used in which the luminescent area of the LED is projected into the flow under investigation using condenser lenses. A combination high magnification and large lens aperture limited the depth of field

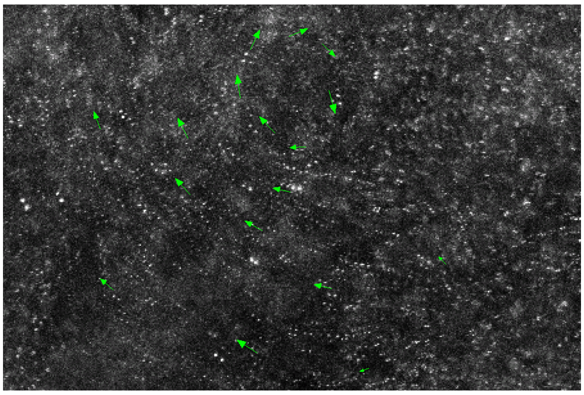

Figure 3: Portion of high magnification PIV recording obtained with LED illumination in forward scatter. A mean horizontal displacement of 14 pixels is subtracted

in the sub-millimeter regime and permitted two-component PIV measurements on an area of about $9 \times 7\,\text{mm}^2$. A 5W-class green LED (LXHL-PM02) was pulsed at $I_f = 2\,\text{A}$ for 20μs. PIV measurements were reliable using 10μm particles in water, imaged by a cooled, double-shutter CCD camera.

Later PIV experiments made use of stronger, projection type LEDs (CBT-40, CBT-120) that could be driven at much higher currents. Figure 3 shows a $3 \times 2\,\text{mm}^2$ portion of a PIV recording obtained in a free jet in air seeded with $1-3\mu$m glycerine droplets. Volume illumination was provided by the CBT-120 LED device using 30 A pulses of 2μs duration. The pulse delay was $\tau = 15\mu$s. Arranged in a 45° forward scattering with respect to the LED light a macro lens (Nikon Nikkor MF 55mm/f2.8) with aperture set at $f\sharp 4$ imaged the flow onto the actively cooled sensor (1376×1040 pixel) of a double-shutter CCD camera (PCO Sensicam QE) using a magnification of approximately 1:1. Assuming a circle of confusion of 5 pixel the depth of field is estimated to be 500μm. The processed PIV data set shown in figure 4 was analyzed using sampling areas of 48×48 pixel ($320 \times 320\mu\text{m}^2$).

While these PIV measurements demonstrate the feasibility of imaging micron-sized droplets in air at moderate velocities using rather short illumination pulses, the method of volume illumination has the drawback of introducing significant background signal due to the light scattered by out-of-focus particles. This reduces image contrast and poses a general problem for micro-PIV applications. Therefore possibilities of converting the highly divergent light of the LEDs into a light sheet were investigated in a next iteration.

The most promising experiments were performed when the LED light was bundled into a light sheet by means of a fiber-optic illumination system, also known as line light. As illustrated in figure 5 the entry side of the fiber bundle is round while the fibers are arranged along a line at the distal end. This line is collimated to form a light sheet using a short focal length cylindrical lens.

Figure 6 provides sample PIV results from a time series of a propeller flow in water acquired at a frame rate of 1.5 kHz using pulsed LED-illumination and a high-speed CMOS camera (Photron, APX-RS, with Nikon Nikkor MF 55mm/f2.8 lens). The water was seeded with 10μm hollow glass spheres. The light sheet thickness was approximately 1 mm a the waist widening to about 2 mm at the edges of the 55mm wide imaged area. Current pulses of 16 A and 20μs duration were used. Based on figure 6 the pulse duration could have been reduced to

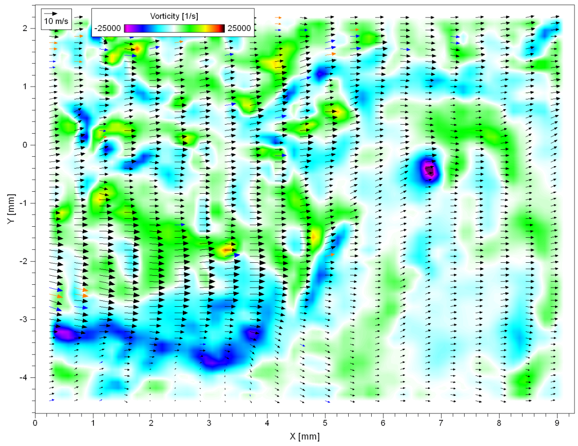

Figure 4: Processed PIV data set corresponding to figure 3 obtained with LED illumination. Horizontally only every fourth velocity vector is shown; orange vectors indicate interpolated data

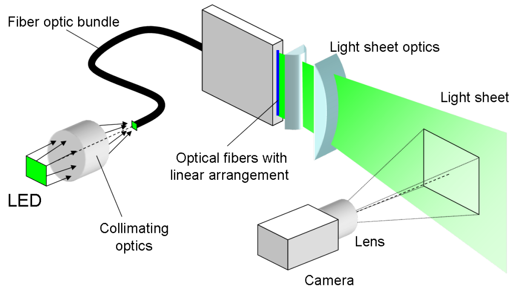

Figure 5: LED-based light sheet illumination using fiber optic assembly

10μs using pulses of 40 A (A suitable high current source was not available at the time of the experiment).

Prior to PIV processing the recorded images were subjected to image enhancement involving background subtraction and minor blurring to reduce spurious noise. The particle image density was sufficient to sample the image with 16×16 pixel sub-windows, corresponding to $0.84 \times 0.84\,\text{mm}^2$.

5. DISCUSSION

The previously described experiments clearly demonstrate the viability of using pulsed, high power LEDs as illumination sources for PIV. Generally being a non-collimated light source is one the more critical drawbacks of the LED. This makes it difficult to establish light sheet illumination commonly found in macroscopic PIV applications unless additional optics such as the fiber optic line lights are used. Unfortunately the large aperture of the LEDs (N.A. ≈ 0.22) does not match well to the smaller aperture of optical fibers (typ. N.A. = 0.22), such that a significant amount of light is lost. Comparable measurements between volume illumination and light sheet illumination indicated that about three quarters of the light is lost by the fiber transmission system.

On the other hand it is viable for LEDs to provide volume illumination for microscopic PIV or photogrammetric particle imaging methods such as tomographic PIV or 3-D particle tracking. In comparison to most pulsed lasers the light pulses can be ‘fired’ nearly immediately. There is no lead time as

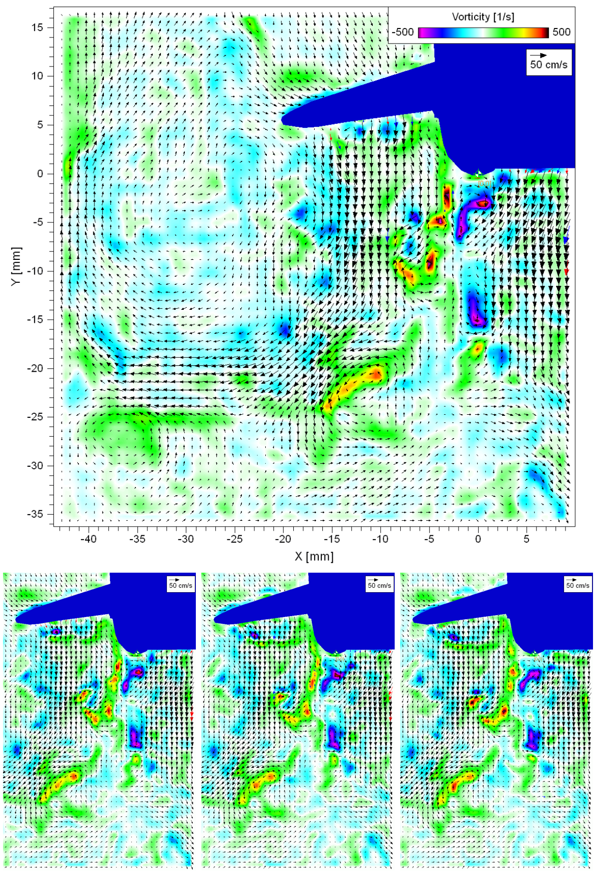

Figure 6: Four consecutive PIV maps from a time-resolved image sequence acquired at 1.5 kHz for a propeller flow inside a small water tank. Separation between displayed recordings is 1.33 ms. For better visibility only one fourth of the vectors are displayed

with lasers to 'pump' the lasing medium. Also the repetition rate can be freely varied since it is not necessary to adhere to fundamental pulsing frequencies. Pulse-to-pulse intensity and spatial variations are practically not present. The broad spectral intensity distribution of the LED's electroluminescence prevents the creation of speckle (interference of coherent light). From a handling point of view the un-collimated light of LEDs is less dangerous, but not necessarily eye-safe, while supply voltages are considerably lower than for pulsed lasers.

6. CONCLUSIONS

The use of LED based illumination for flow measurement was investigated on the background of a possible alternative to commonly used laser based illumination. The study was motivated by the recent availability of high power LEDs with continuous radiant flux levels comparable to that of lasers. Pulsed light at significant intensity levels can be obtained from these solid state devices by briefly overdriving them with high currents. This permits PIV measurements in both water and air.

Challenges yet to be solved are associated with the rather wide-angle radiation pattern (i.e. high N.A.) of the light issuing from the luminous surface of the LED. The high numerical aperture restricts the creation of thin light sheets comparable to those achieved with the collimated light of lasers. Nonetheless reasonable light sheets could be achieved using a fiber optic collimating device with which time resolved PIV measurements were performed in water at frame rates exceeding 4 kHz (not presented here).

Currently available high power LEDs are particularly well suited for applications requiring volume illumination such as shadowgraphy or even the recently introduced volume resolving, particle based velocimetry techniques (e.g. tomographic PIV or 3D-PTV). PIV systems using LEDs as light sources can be assembled at significantly reduced costs. Compact, battery operated systems are feasible and could be of interest for in-flight measurements or autonomous operation in hazardous environments.

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