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Feasibility analysis and demonstration of high-speed digital imaging using micro-arrays of vertical cavity surface-emitting lasers

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Abstract. Previous laser illumination systems at Aberdeen Proving Ground and elsewhere required complex pulse timing, extensive cooling, large-scale laser systems (frequency-doubled flash-pumped Nd:YAG, Cu-vapor, Q-switched ruby), making them difficult to implement for range test illumination in high speed videography. Requirements to illuminate through the self-luminosity of explosive events motivate the development of a high brightness imaging technique obviating the limitations of previous attempts. A lensed vertical cavity surface-emitting laser array is proposed and implemented with spectral filtering to effectively remove self-luminosity and the fireball from the image, providing excellent background discrimination in a variety of range test scenarios. [DOI: 10.1117/1.3570678]

Subject terms: high brightness imaging; laser illumination; high speed videography; fireball filtering; background discrimination.

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1 Introduction

Requirements were identified for the development of a high speed photographic system to image objects engulfed in high radiance backgrounds, such as the self-luminosity associated with explosion events. Use of laser illumination in conjunction with narrow band pass filtering provides background discrimination for high resolution, high speed digital image processing. In addition, the characteristics of the vertical cavity surface-emitting laser (VCSEL) structures now available represent viable lighting characteristics for other illumination events currently using flashbulbs and argon discharge lamps.

The system must operate under the harsh conditions presented by an explosive test environment and must exhibit sufficient robustness to survive the field test environment. Timing sequences for shuttering, modulation, camera synchronization, exposure time, and digital image frame rate should be integrated with a high degree of accuracy, permitting high resolution, blur-and distortion-free, quantitative video realization of high speed events, and associated data processing. Target illumination power levels should be sufficient to provide imaging of an area of at least 1 m^2.

Laser illumination can be applied in a broad range of test scenarios. In some, it may be necessary to pulse the laser for gated imaging. This technique can be used for 3-D imaging, digital image correlation, and also for improving the signal to noise ratio at a desired imaging depth. In gated imaging, a synchronized triggering signal is sent to both the camera and laser. Short pulses are then emitted from the laser and the reflected light from the scene is accepted at desired time delays. Other applications do not require gating.

There are many areas in which the use of laser illumination is of interest. Detonation events, such as those of shaped charges, small caliber grenades, and explosive projectiles, can be examined to further understand jet formation and particulate properties, fuse function times, and fragmentation patterns. Performance characteristics for various projectiles and explosive threats against passive, reactive, and active target systems can be examined, along with flight and performance characteristics. There are also applications in the areas of both vehicle and body armor, to examine effects of impact and vulnerability from explosive and projectile threats.

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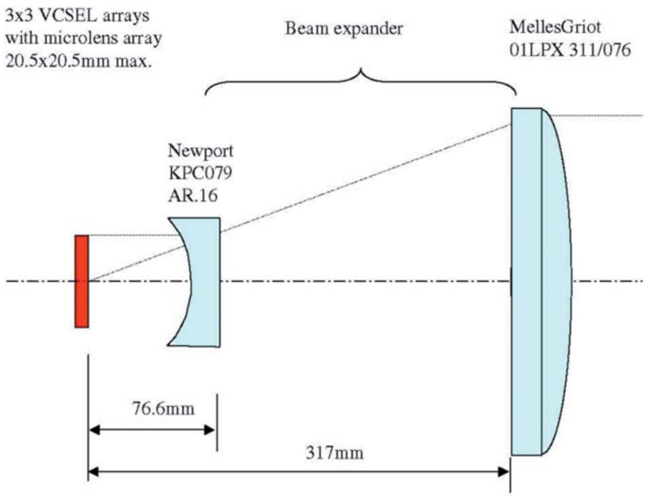

Fig. 1 Example with a collimating lens of focal length = 300 mm.

2 System Design Goals, Parameters, and Assumptions

2.1 *System Design Goals*

The motivation for this system[1–4] is derived from the Aberdeen Advanced Armor Instrumentation efforts, test officer inputs, Army Research Lab applications, and ongoing requirements expressed in the open science grid published technical papers. The goal is to develop a portable system for use on a variety of test range illumination events. The system will use as much commercial off-the-shelf (COTS) equipment as possible to reduce overall cost, time, and life cycle maintenance costs. The ability to survive transportation and use in blast events is important, along with a brass board with standard Phantom high speed cameras. Safety and remote operation are important aspects of design, and will include a turnkey system for maximum acceptance and utilization. The payback period will be minimized while the effective life cycle will be maximized.

2.2 *System Parameters and Assumptions*

1. VCSEL array: 5×5 mm diameter each, self-lasing, 976 nm, 14 deg full divergence angle (0.12 NA); multiple arrays if necessary.
2. Output beam: 20-mrad full divergence angle (1-m beam diameter at 50-m target), use simple low-cost optics without microlens array.
3. Design margin: 0.8 to 1.2-m beam diameter at 50-m target, or 16 to 18-mrad full divergence angle.
4. Design considerations:
   - Different from those using a micro-lens array: the VCSEL array dimension dominates the output beam divergence, not the single emitter divergence (∼2 orders of magnitude smaller).
   - Both segmented and millimetric VCSEL arrays are usable (when using a microlens array comfit, the selection is critical).
5. Preliminary design values:
   - Collimating lens: focal length = 278 to 313 mm, with clear aperture = 72 to 80 mm, placed at the back focal plane.
   - For multiple 5×5-mm arrays, may use a macro-lens array with focal length and pitch of the lens diameter
   - Lens/VCSEL-array tolerances: $dz \sim 1$ mm: $\sim +$ 0.8-mrad divergence, or 5% beam diameter change at 50 m; dx, $dy \sim 1$ mm: output beam pointing change ∼ 0.2-m at 50-m target. Longer focal length lens is usable if room allows; beam divergence and beam diameter at target can be adjusted by the lens detuning.
6. Optical schematic: example with a collimating lens of focal length = 300 mm (Fig. 1).

3 Current Capability

Two key technologies are utilized to achieve adequate scene illumination for high speed video capture of test range events: flashbulbs and discharge tubes. Output curves for the frequently used PF-200 and PF-300 flashbulbs are shown in Fig. 2. The peak output of 6.0×10^6 lumens translates to 477465 candelas. Bulbs are flashed at 28 ms prior to the key portion of a video stream, so that for a 5 to 10 ms window, the target scene is illuminated at or above 90% of the peak flash output. The timing of the peak flash output and the character of the flash event are confirmed with .cine files obtained with a Vision Research Phantom v7.3 high speed digital imaging

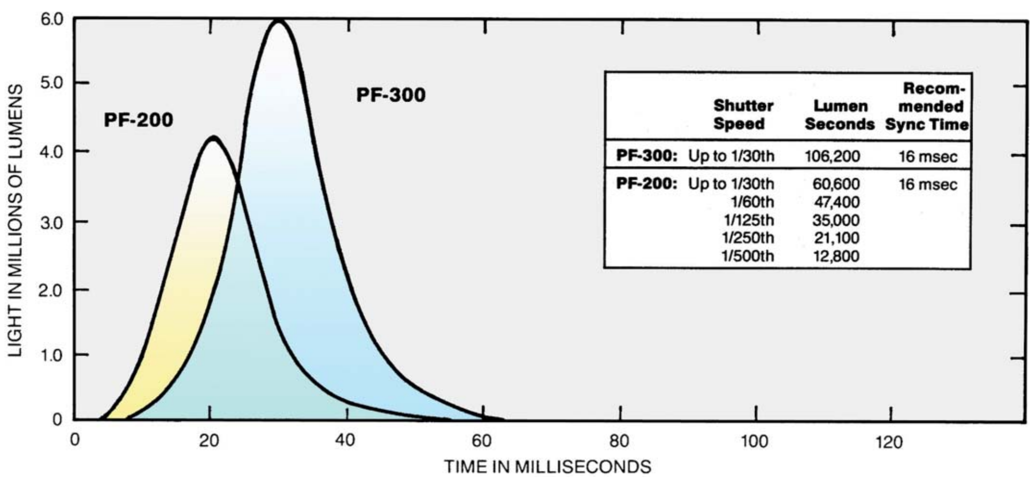

Fig. 2 Output curves for the frequently used PF-200 and PF-300 flashbulbs.

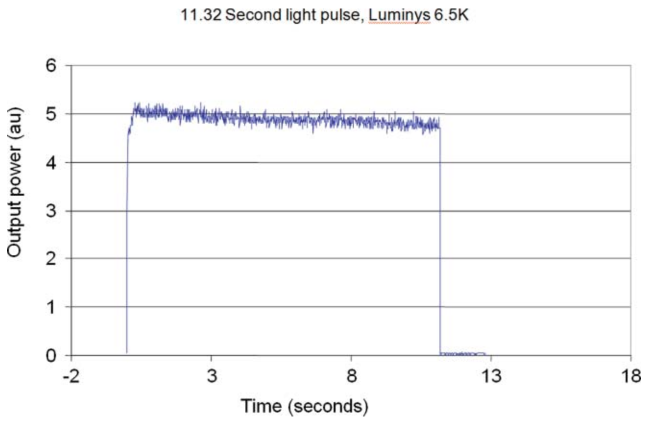

Fig. 3 Time history of Luminys Corporation's 6.5-K light system.

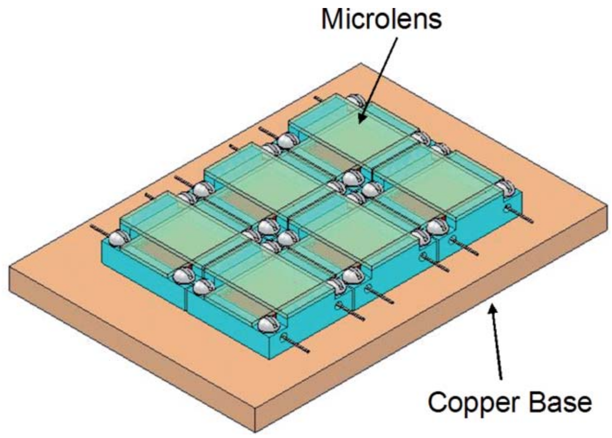

Fig. 4 6-VCSEL array configuration (current configuration contains nine).

system, as well as several photometers at the Aberdeen Center for Sensing Technology.

The next-brightest light source, arc discharge tubes, currently identified and used for high speed imaging, the Luminys Corporation 6.5-K Blast high intensity light, produces 25863 candelas, but for a significantly longer duration, depending on the charging characteristics. A typical illumination event for the 6.5-K Luminys light is shown in Fig. 3.

4 VCSEL

4.1 *VCSEL Technology*

VCSELs were historically limited to low-power applications until, through several Defense Advanced Research Projects Agency sponsored programs.[5] Princeton Optronics Corporation developed the world's highest power single devices and 2-D arrays.[6] They have successfully demonstrated single devices with >3 W continuous wave (CW) output power and large 2-D arrays with >230 W CW output power. These arrays are comprised of thousands of small, low power, single mode devices. The output of this array can then be focused into a very small, low-diverging spot using a microlens array focusing-lens system. VCSELs have several major advantages in our application[6]:

- A circular output beam.
- Much lower wavelength-dependence to temperature (5× less than for edge-emitters). Since the VCSEL resonant cavity is defined by a wavelength-thick cavity sandwiched between two distributed Bragg reflectors, devices emit in a single longitudinal mode and the emission wavelength is inherently stable (<0.07 nm/K), without the need for additional wavelength stabilization schemes or external optics, as is the case for edge emitters.
- A much higher reliability than edge emitters since VCSELs are not subject to catastrophic optical damage failures.

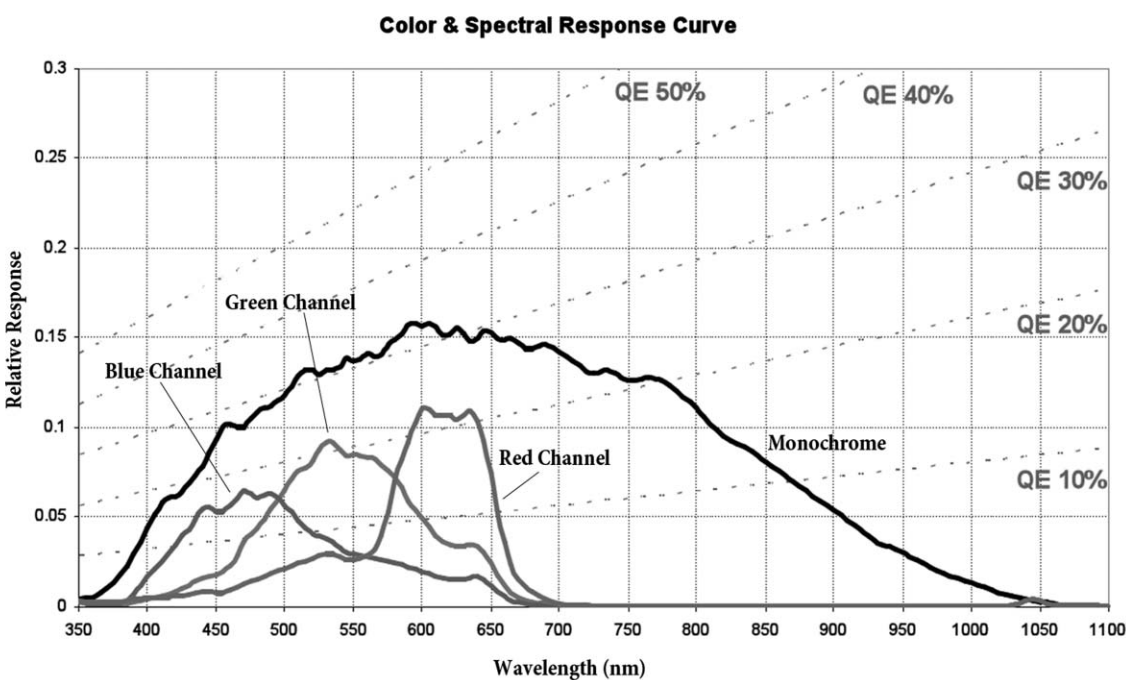

Fig. 5 Spectral sensitivity of Phantom v7.3 high speed digital imaging system (Provided courtesy of Richard Toftness at Vision Research).

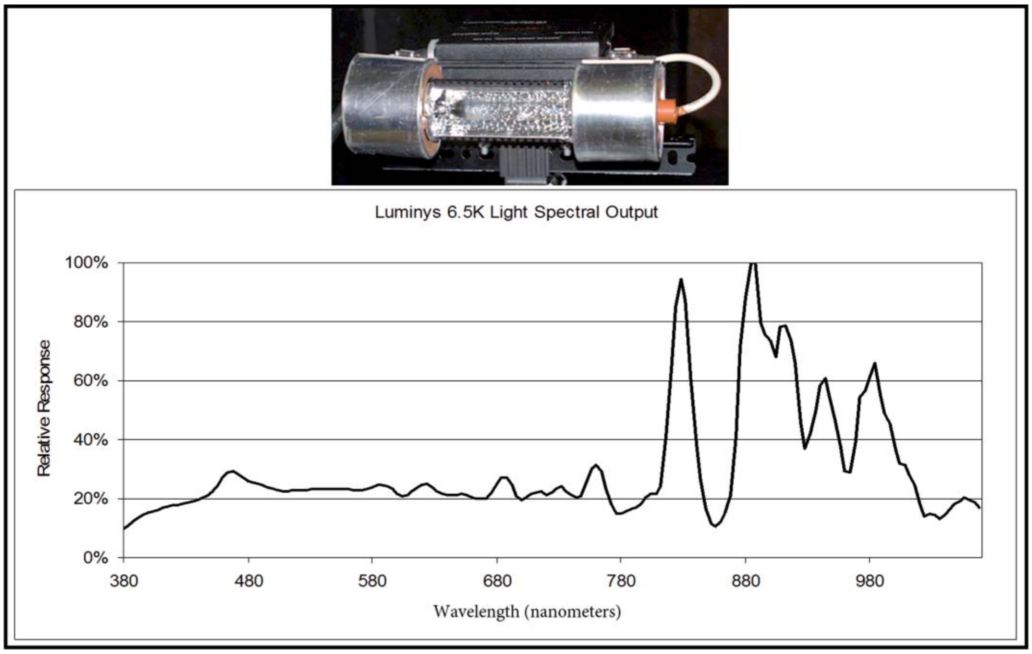

Fig. 6 Normalized spectral output of Luminys Corp. 6.5-K light.

- High temperature operation. VCSELs and VCSEL arrays can be operated at temperatures up to 80 °C ambient without chillers.
- High power from the arrays (demonstrated CW power density of 1200 W/cm^2 from the arrays).
- Emission wavelength is very uniform across a 5×5 mm VCSEL array, resulting in spectral widths of 0.7 to ∼0.8 nm full width at half maximum (FWHM).
- VCSELs can be easily processed into large 2-D arrays (does not need stacking) to scale up the power. The 2-D array configuration provides for more efficient heat-sinking and better pump power density, as the devices can be very closely packed.
- Low thermal resistance for CW operation. A thermal resistance of 0.15 °C/W from the junction temperature to the microcooler coolant makes it lower by more than a factor of 2 compared with edge emitter arrays.
- VCSEL arrays are designed for coupling match to COTS microlens arrays.
- Princeton Optronics makes single mode devices at wavelengths of 976 and 1064 nm, as well as custom wavelengths between 808 and 1064 nm.

4.2 *Preliminary Performance Considerations*

As a starting point, we consider the optical output needed to achieve a luminous intensity comparable to that of the arc discharge lamp (25000 lumens). In measurements performed at Aberdeen, a single VCSEL array driven at 98 A delivered 70 W at 976 nm. Using the well-known conversion of 1 W = 680 lumens at 550 nm (Ref. 5), and a correction factor of 7 [assuming a camera quantum efficiency (QE) of 35% at 550 nm and 5% at 976 nm], the equivalent single-VCSEL output at 976 nm is about 6800 lumens. A 9-VCSEL device will deliver about 61,200 lumens of focused light onto its target. It can be expected for the VCSEL to improve lighting by more than one f-stop, and the source can be used at extended distances.

The arrays are connected serially and mounted on a copper base (Fig. 4). For 150-ms operation, the heat released is about 9 J. The specific heat of copper is 0.385 J/g °K; therefore, for 100 g of copper submount the temperature increase is only 2.5 °C, which allows passive cooling.[7–10]

4.3 *Flexibility of Approach*

Nebolsine et al.[2] developed estimates for shaped charge jets and radiometric characterization of video cameras. The approach was to determine illumination levels for a laser illuminator needed to overcome the jet luminosity and provide sufficient exposure for imaging. This was used to evaluate candidate laser technologies for suitability in system design. The VCSEL approach provides flexibility, in that it can be

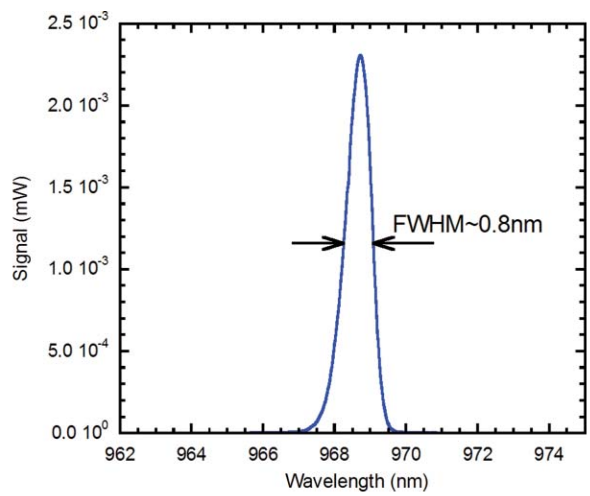

Fig. 7 Spectral output of a VCSEL array at ∼100 W CW output (Provided courtesy of Princeton Optronics).

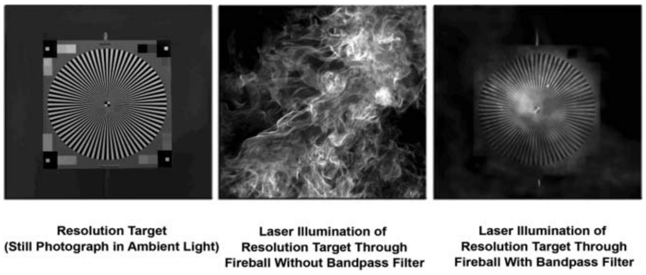

Fig. 8 Laboratory demonstration of nine VCSEL illuminator using Photron SA5.

utilized in a range of timing and illumination test scenarios. The pulse length can be essentially CW, with minimal cooling requirements; while the illumination brightness can be increased through the addition of more arrays in the package configuration.

5 Spectral Matching Considerations

The monochrome spectral response curve for the Vision Research Phantom v7.3 high speed video camera used in our brass board benchmark is shown as the dark curve in Fig. 5. While light sources such as the Luminys 6.5-K lamp, for example, exhibit broadband spectral content (Fig. 6), similar to the flashbulbs, VCSEL sources produce a nominal 976-nm center wavelength, with a FWHM spectral width of 0.8 nm (Fig. 7). The significance of having the VCSEL optical power concentrated within the filter window is of course to maximize the useable portion of the illuminator's output while eliminating the interference of the event's blast. Also for this reason, the response of the v7.3 at 976 nm is an important parameter for our system design. As mentioned previously, the ratio of the quantum efficiency at 550 nm to the efficiency at 976 nm is about 7.

6 Discussion

The system developed is intended for a wide variety of illumination scenarios. The VCSEL can be pulsed and operated, without being cooled, for the duration of short events (e.g., 150 to 200 ms), as was the case with previous work in laser illuminators, where the light source determined the temporal sample size for the event. For longer event applications it can be operated CW and in a cooled configuration. In CW operation, the temporal characteristics of high speed capture are determined by the camera.

Use of VCSELs for laser illumination applications shows great promise as a versatile, readily implemented approach to a host of current challenges for high speed imaging on the Aberdeen ranges. A technology demonstration phase utilizing a nine VCSEL array has been performed in our laboratories. A view from the demonstration is shown below in Fig. 8, in which a resolution target was imaged in various configurations to include laser illumination and bandpass filter usage. The images were captured with Photron SA5 cameras using a Nikon f 2.8, 200-mm lens at a standoff distance from the target of approximately 25 ft. The image in the middle has no filter in front of its lens, while the image on the right is

Fig. 10 Fielded brass board 9-VCSEL model.

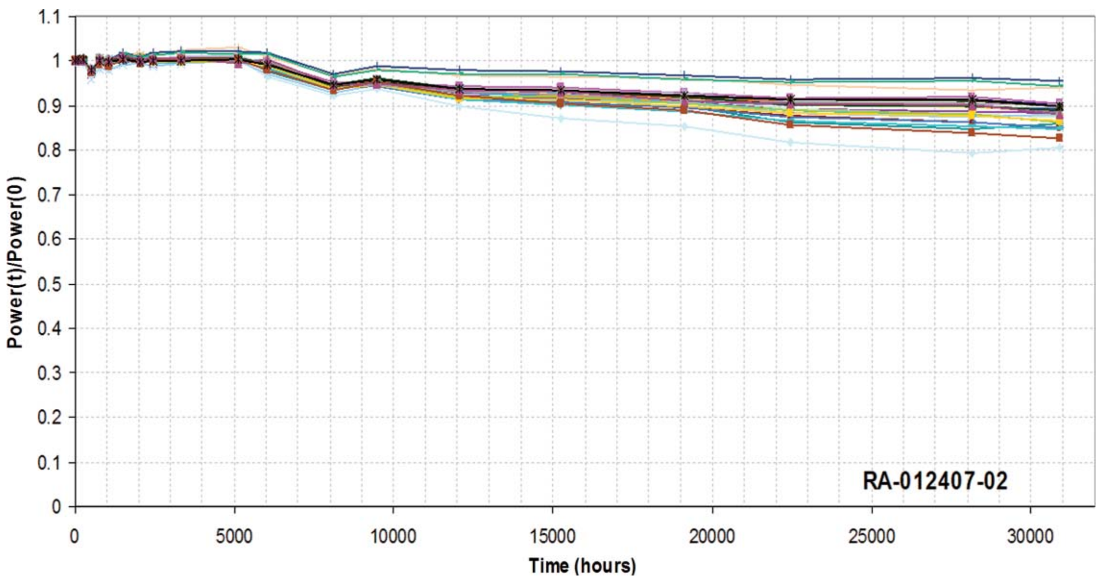

Fig. 9 Accelerated lifetime data for 29 VCSELs at 73C, failure-free operation for > 3.5 yrs. (Provided courtesy of Princeton Optronics).

from a camera with a 976-nm ± 4-nm bandpass filter. The utility of the VCSEL illumination is readily apparent.

In addition to providing visibility through fireballs, the VCSEL source is not expended during an event like flash bulbs. In fact there is life and stability data available at elevated temperatures, to simulate accelerated aging. Data for 29 VCSELs is shown in Fig. 9. These devices operated failure-free for an equivalent time of >3.5 yrs. The high-stability, long-lifetime pedigree is characteristic of a component that hails from the telecom technology sector.

A fielded brass board 9-VCSEL model, shown in Fig. 10, is now in testing in live fire applications, protected by bombproof enclosures and Lexan acrylic sheets to survive ballistic and explosive events. The system performance requirements and specifications were determined by the Army labs and provided to Princeton Optronics for collaborative design realization.

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