High-definition Broad-band Visible-SWIR Sensors for Laser Mark Detection

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Abstract

Shortwave infrared (SWIR) sensors are a key component of modern-day laser designation and surveillance systems; allowing the warfighter to covertly acquire and target adversaries with common infrared laser wavelengths including 1064 nm and 1550 nm. SWIR VISION SYSTEMS® builds high-resolution sensors using colloidal quantum dot (CQD®) photodiodes sensitive across the spectral band from 400 to 2000 nm. CQD technology provides the ability to image common designation lasers while simultaneously offering the benefits of high-pixel-count imagers – including wide fields of view and more pixels on target. To demonstrate the utility of the CQD detector technology for this application, SWIR Vision has carried out tests imaging short pulse lasers in outdoor environments using its ACUROS® HD camera. These tests were carried out side-by-side with a commercially available InGaAs camera. This paper will show the results of this testing and provide a comparison of the performance, range, and pulse-power requirements for designation applications using CQD and InGaAs technology. As the importance of SWIR laser designator systems in the modern battlespace continues to grow, SWIR CQD technology shows promise to differentiate and maintain an advantage over our adversaries both with higher resolution imagery as well as the ability to detect wavelengths longer than what has traditionally been possible by traditional IR detector technologies.

CQD Detector Performance as it Relates to Technical Requirements for Laser Detection Systems

Introduction

SWIR VISION SYSTEMS thin-film photodiode array technology uses a colloidal quantum dot (CQD) broadband absorber with a tunable band gap from the near-infrared (NIR) to extended shortwave infrared (eSWIR). Today, SWIR Vision Systems produces cameras with visible (Vis)-SWIR response from 400 to 1650 nm and Vis-eSWIR cameras which are sensitive from 350 to 2100 nm. Owing to the power of parallel processing (i.e. monolithic process on 8 or 12” Si CMOS ROICs), standard CMOS deposition and patterning techniques (e.g. sputter, evaporate, spin coat), and the mature colloidal quantum dots ecosystem for the QLED display market, our CQD fabrication approach results in a straightforward path for fabricating SWIR and eSWIR FPAs at high volumes and low cost.

Laser range finding, marking, targeting, and designating are now ubiquitous on the modern battlefield. The need for more covert and eye-safe systems is pushing system designers to look deeper into the infrared spectrum, shifting from the NIR to the SWIR and e-SWIR wavelengths. InGaAs FPAs are being widely adopted in mounted systems that can afford the relatively high price points (e.g. armored vehicles, aircraft, naval vessels), but are generally too expensive for dismounted troop-level systems like rifle scopes or XR headsets. As InGaAs detector fabrication becomes more commonplace around the world, the standard SWIR wavelengths are becoming less covert. With its best-in-class uncooled signal-to-noise performance in the 1.7–2.0 μm range, the CQD eSWIR detectors open another portion of the uncooled infrared spectrum. This paper explores the feasibility of using CQD technology to meet the need for SWAP-C laser detection devices in the SWIR and eSWIR spectrum.

Technical Requirements

The specific requirements for laser detection vary by application, but in general, the signal reflecting off of the objects of interest must exceed the sum of the noise sources (e.g. dark current, read noise, solar background, etc). In many cases, the detectors must be fast enough to extract temporal information from the return signal (e.g. laser range finding, ALPD decoding), and in all cases, the devices must survive MIL-STD accelerated lifetime testing.

The setup described in Figure 1 below was used to estimate the rise/fall time of the CQD photodiode. A 5 Hz pulsed 1064 YAG laser was measured with both our CQD detector and a reference InGaAs detector. Using this setup, rise/fall times of less than 5 ns were measured on SWIR VISION SYSTEMS CQD detectors. For laser range-finding applications, response times of 5 ns equate to 1.5 m of spatial resolution, which exceeds the requirements for most long-range LRF systems. We'd note, that a 5 ns fall time is not seen as the lower limit for these detector's time response, but instead, likely represents the limits of the measurement setup. ALPD systems typically operate at around 20 Hz, many orders of magnitude below our CQD detector's measured rise/fall times. CQD detectors appear to have rise/fall times that significantly exceed the typical requirements for laser detection applications.

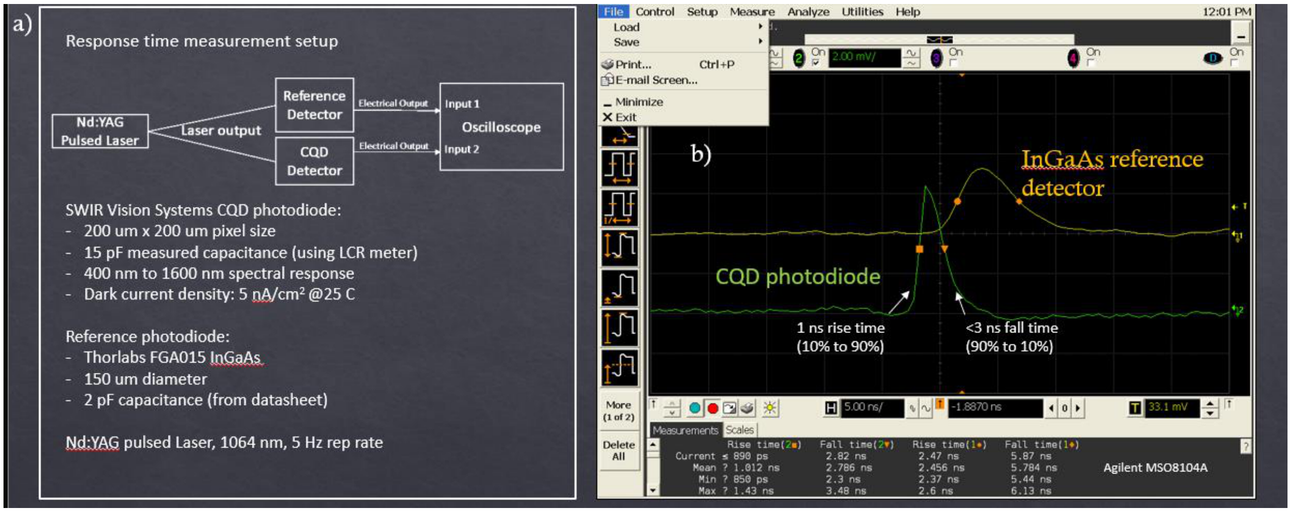

Figure 1. a.) Description of High-speed Test Setup Used to Estimate Rise and Fall Times of CQD Photodiode. b.) Oscilloscope Output of CQD (Green) and InGaAs Reference Photodiode (Yellow)

To ensure laser detection systems will perform reliably in the field, they must survive thermal and mechanical MIL-STD accelerated stress tests. CQD detectors do not rely on hybridization or any other novel mechanical connection or interface which would make them particularly sensitive to mechanical stresses. Vibration tests completed on the Acuros camera suggest the wire bonds fail before any of the mechanical interfaces in the CQD photodiode stack. To meet the typical MIL-STD requirements, SWIR Vision Systems has optimized its CQD detector technology to be compatible with longestablished downstream packaging approaches (e.g. wire-bond, die-attach, solder reflow, color filter, etc). A demonstration of this compatibility can be seen in Figure 2 wherein a 1.2MP CQD image sensor was subjected to a 200C solder reflow. Using EMVA1288 test protocols, all merits of interest (QE, Jd, PRNU, DSNU, linearity, etc) remained within standard tolerances.

Figure 2. Image from ACUROS 1.2MP Image Sensor After Wire-bond, Die Attach, and 200C Solder Reflow Cycle

The thermal stability of the CQD detectors has also been investigated. As can be seen in Figures 3 and 4, after optimization of the fabrication process, the CQD devices exhibited stable QE and dark current performance at both 85 °C / 85% RH and 125 °C storage. While additional thermal stress testing is needed to ensure reliable operation in the field, this demonstration is promising.

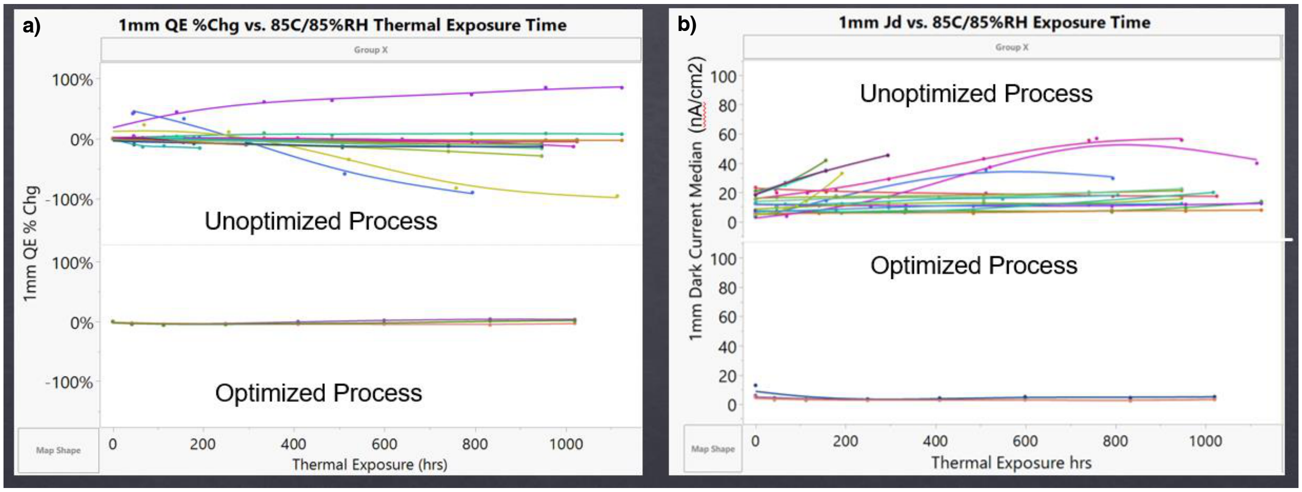

Figure 3. Results of 85%RH / 85 °C Accelerated Stress Testing.
a) %QE Change (Relative) as a Function of Stress Time.
b) Dark Current Values as a Function of Stress Time

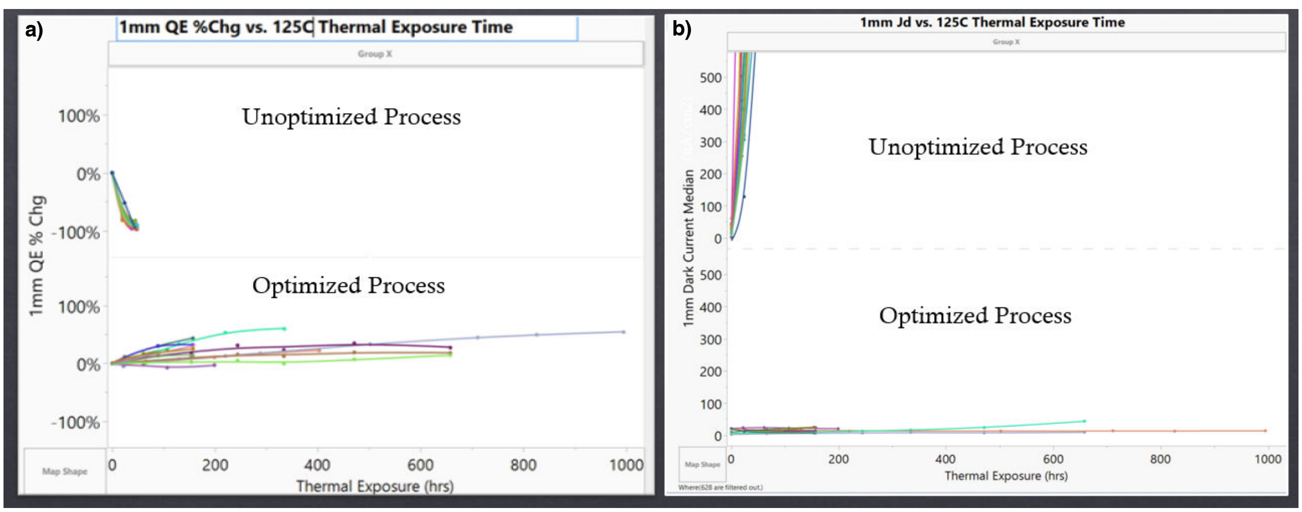

Figure 4. Results of 125 °C Accelerated Stress Testing.
a) %QE Change (Relative) as a Function of Stress Time.
b) Dark Current Values as a Function of Stress Time

The signal-to-noise ratio is another key metric for laser detection applications. The CQD detector's read and dark current noise are similar to traditional InGaAs detectors, approximately 65 e^- for a 15 μm pixel in high gain mode and 5 nA/cm^2 respectively. However, the quantum efficiency of CQD detectors in the current generation ACUROS cameras is significantly lower than typical InGaAs FPAs (see Figure 5). The primary objective of this work was to evaluate the feasibility of these lower QE detectors in laser detection applications.

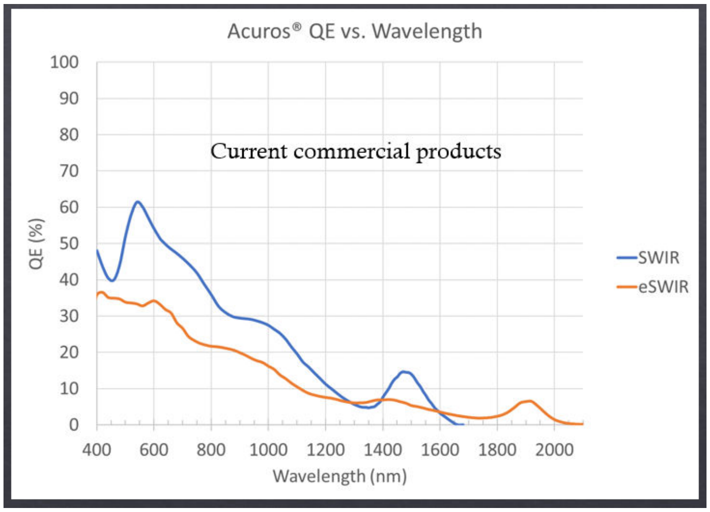

Figure 5. Spectral External Quantum Efficiency Plots for Existing CQD ACUROS SWIR and eSWIR Image Sensors

Experimental Setup

Laser Range and Emitter Details

The demonstration described herein was carried out at a dedicated long-range laser detection test site. As described in Figure 6, a 1535 nm laser emitter was co-located next to our CQD ACUROS camera. The laser was pointed at various targets down range. The laser-emitted photons are reflected from the downrange targets back to the CQD detector. Targets of various sizes, ranges, and reflectivities were imaged and are described in Table 1. The evaluation was done on a “cloudless” day with an air temperature of roughly 60 °F.

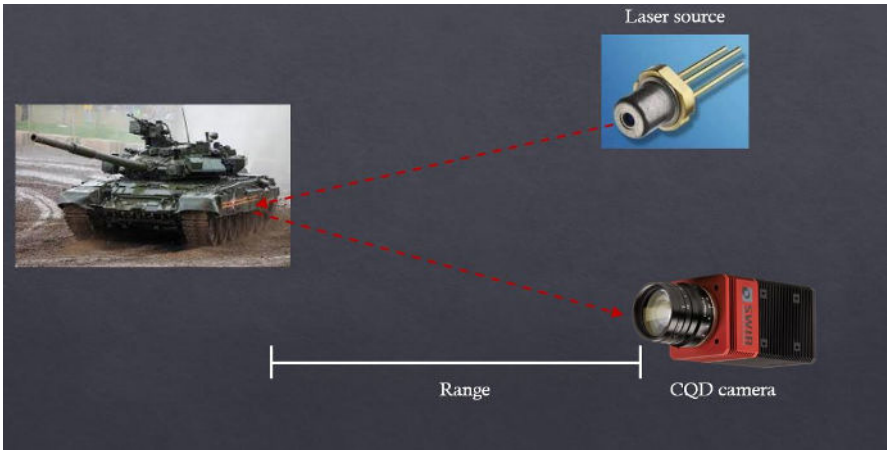

Figure 6. Cartoon Describing the General Setup of the Laser, Target, and Camera

Figure 7. Visible Image of the Range. This Image was Captured from the Position of the ACUROS Camera and Laser Emitter

Table 1. DESCRIPTION OF TARGETS IMAGED ON THE LASER RANGE

Target	Description	Range (m)	Size	Reflectivity
1	NATO target	200 m	2.4 x 2.4 m	~10%
2	NATO target	1000 m	2.4 x 2.4 m	~10%
3	Tank	1800 m	Tank	30–40%
4	NATO target	2000 m	2.4 x 2.4 m	~10%

A 5 mJ laser range finder / marker was as a photon source. The emitter wavelength was centered at 1535 nm to match the band pass filter. The pulse width was approximately 15 ns at a 5 Hz repetition rate. The divergence was specified at 0.4 mrad.

ACUROS CQD Camera Setting

Images were captured with a CQD ACUROS-1920-GigE-001 camera. The camera contains a 1920 x 1080 format CQD sensor made-up of 15 x 15 mm pixels. The readout integrated circuit (ROIC) in the ACUROS cameras does not have ALPD capability. In lieu of ALPD capability, a short exposure time of 0.5 ms was chosen to maximize the laser signal from the background solar signal. Using the external trigger, the camera was synchronized with the laser emitter, ensuring a single laser pulse fell within the 0.5 ms exposure time. A high analog gain mode with a well-depth of 25 Ke^{-} was selected to increase sensitivity. A 100 mm f/2.1 SWIR optimized lens was used with a 1535 nm band-pass filter with >60% peak transmission and a 10 nm full-width half max. The onboard single-stage TEC inside the CQD image sensor package was set to 10 °C.

InGaAs Camera Setting

For comparison purposes, a 640 x 512 resolution InGaAs camera with 15 x 15 mm pixels was used to collect side-by-side images. Exposure time (0.5 ms) was matched to the ACUROS setup. A duplicate of the lens used with the ACUROS test was not available, so an 83 mm f/2.6 SWIR-coated lens was paired with the InGaAs camera. The InGaAs camera used for this experiment did have onboard ALPD functionality which eliminated the need for a 1535 nm band pass filter.

Results

Laser Spot Detection with CQD Camera

The ACUROS 1920 GigE 001 camera with the CQD detector technology was able to image the laser spot at all ranges of interest, from 200 to 2,000 meters. Images collected with the CQD camera are shown below in Figures 8−11. Two images are shown at each range, one with the full 1920 x 1080 resolution and a cropped image to highlight the pixels on target. Noise can be seen at the edges of the frame due to vignetting of the lens. Image quality could be further improved with the implementation of an optimized two-point non-uniformity correction algorithm.

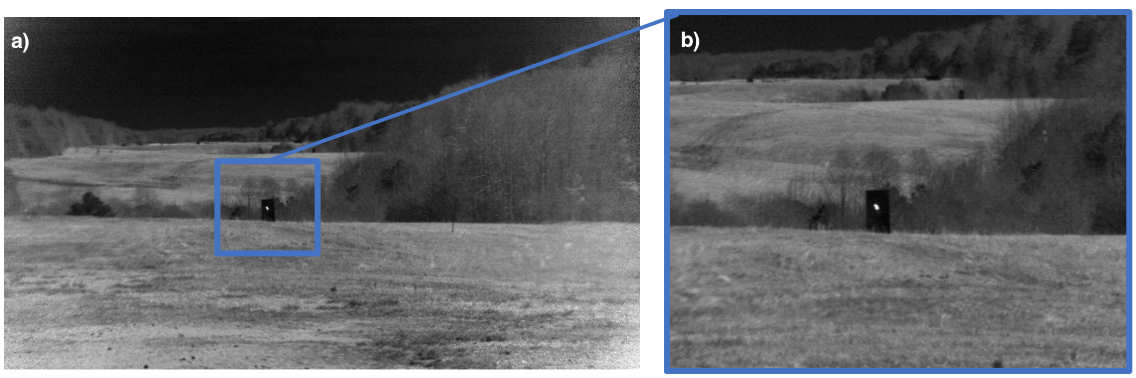

Figure 8. ACUROS-1920-GigE-001 Imaging 1.5 μm Laser Spot on NATO Test Target at 200 Meters.
a) Full Resolution Raw Image b) Cropped Image to Highlight Region of Interest

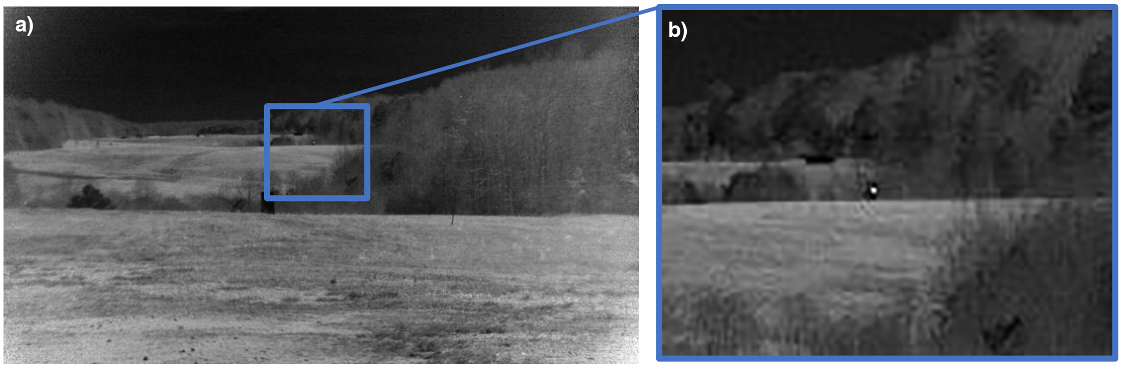

Figure 9. ACUROS-1920-GigE-001 Imaging 1.5 μm Laser Spot on a NATO Test Target at 1000 Meters.
a) Full Resolution Raw Image b) Cropped Image to Highlight Region of Interest

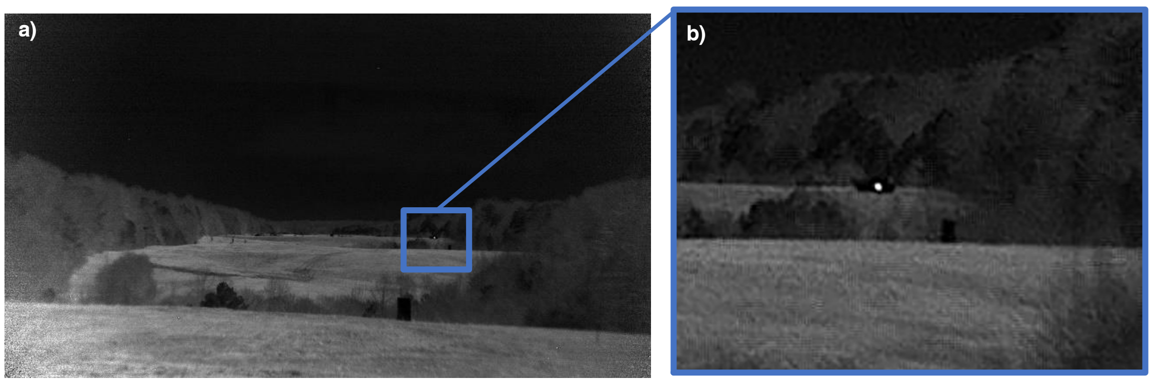

Figure 10. ACUROS-1920-GigE-001 Imaging 1.5 μm Laser Spot on a Tank at 1800 Meters.
a) Full Resolution Raw Image b) Cropped Image to Highlight Region of Interest

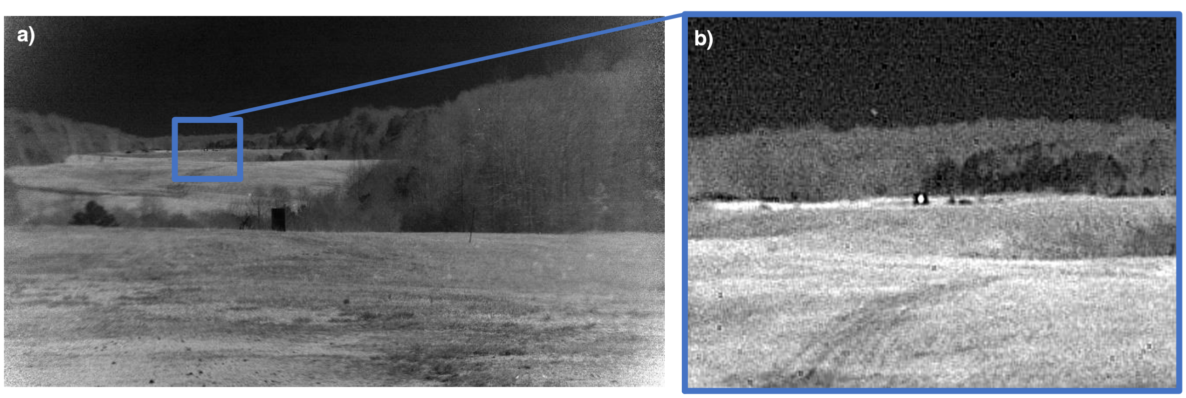

Figure 11. ACUROS-1920-GigE-001 Imaging 1.5 μm Laser Spot on a NATO Test Target at 2000 Meters.
a) Full Resolution Raw Image b) Cropped Image to Highlight Region of Interest

InGaAs Comparison

As can be seen in Figure 12 below, comparison images were also collected with a 640 x 512 InGaAs camera. The InGaAs camera is equipped with an ALPD-capable ROIC. With ALPD capability, any pixel which detects an AC response, like a laser pulse, is assigned a value corresponding to saturation (e.g. 256 on an 8-bit scale). This “image processing” allows the laser-illuminated pixels to appear brighter than the surrounding scene. The ALPD-capable ROIC also eliminates the need for a 1535 nm bandpass filter, enabling significantly higher photon fluxes from the surrounding scene. The InGaAs camera also implemented a 2-point optimized NUC to reduce fixed pattern noise.

One of the standout features of the CQD camera is its industry-leading 2.1 MP resolution, enabling broader fields of view (FOV) and/or more pixels on target. In this demonstration, lenses of similar focal lengths (100 vs 83 mm) were chosen, resulting in a similar number of pixels on target. At a range of 200 m, the InGaAs camera had 4,444 pixels on the 2.4 x 2.4 m NATO target, while the ACUROS had 6,400 pixels on target. When using lenses of similar focal lengths, the FOV advantage of the 2.1 MP resolution is significant. At 200 m range, the 640 x 512 InGaAs sensor has a FOV of 23.1 x 18.5 mm or 0.4 km^2 while the 2.1 MP ACUROS camera has a FOV that is approximately 4.3 x larger, 57.6 x 32.4 m or 1.8 km^2. In this application, larger FOVs would allow the user to locate the lasers on the field more quickly with greater situational awareness.

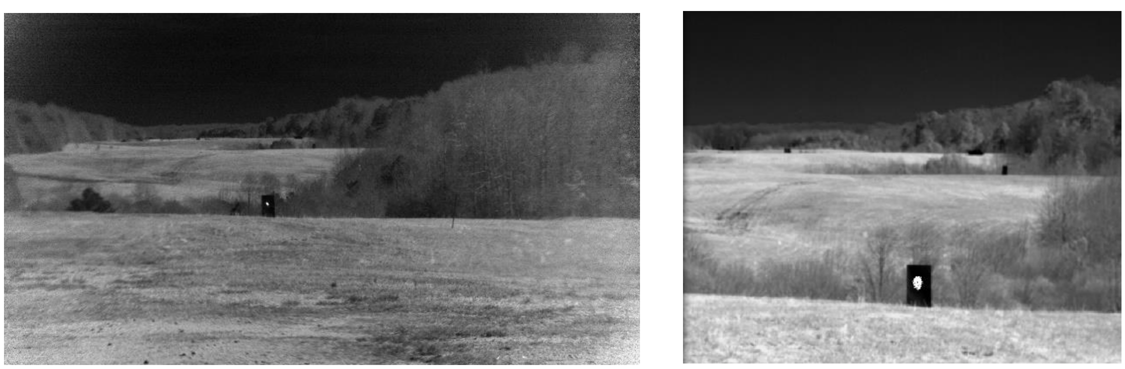

Figure 12. Comparison of CQD (Left) and InGaAs (Right) Cameras Imaging 200 m Target

Conclusions and Outlook

In this work, we demonstrated the use of ACUROS cameras, powered by CQD detector technology, to image SWIR laser spots at ranges out to 2,000 m. This demonstration was performed in full sunlight, which is one of the most challenging environments for laser imaging applications. With its ability to scale much lower costs and smaller form factors than the incumbent InGaAs technology, the CQD detector technology is well-positioned to address cost-sensitive laser spot imaging applications.

To meet the emerging needs of warfighting applications, the SWIR Vision System's roadmap includes the development of higher QE detectors, broader bandwidth detectors with sensitivities beyond 2000 nm, higher resolution focal plane arrays, and ALPD-capable devices. In the near term, SWIR Vision is set to commercialize a new enhanced-QE CQD photodiode structure resulting in a 2-4x enhancement. An example of the resulting QE curve from a 1480 nm QE-enhanced CQD photodiode is shown below in Figure 13. The increased QE and SNR will enable longer-range imaging and better performance in low-light conditions.

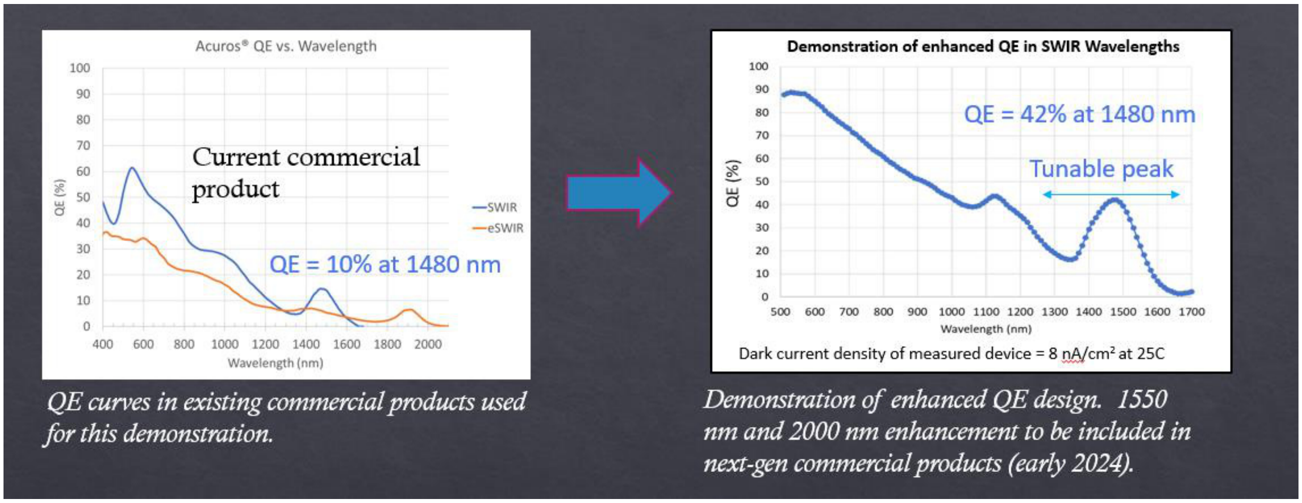

Figure 13. Demonstration of QE Enhancement on the Existing Commercial Product (Left) and with Future QE Enhancement (Right)

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