Laser Imaging Using Short Wave Infrared (SWIR) Image Sensors

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Introduction

Laser based technology has become ubiquitous technology enablers responsible for all manner of modern marvels such as industrial machining, telecommunications, terrain mapping, and medical imaging to name just a few applications. Behind each of these modern innovations lies an advancement in laser technology. One of the primary methods through which the field of laser physics advances is through the imaging of laser emission using image sensors. At SWIR VISION SYSTEMS® (SVS), we are enabling the next wave of laser innovation by pioneering imaging capabilities that span the full Short-Wave Infrared (SWIR) spectra and even extend down through the visible into the UV spectra. In this paper, we explore how high resolution, wide field-of-view, and extended SWIR (eSWIR) ACUROS® cameras are being utilized not only to advance new laser product development, but also to enable new and exciting laser imaging applications.

SWIR Imaging and ACUROS CQD Sensors

The SWIR spectrum ranges from around 900 nm out beyond 2 μm and offers several uniquely beneficial performance attributes compared with the visible spectra. Exotic material requirements combined with limited market volumes have generally led to higher prices and restricted options for SWIR based image sensors. However, the advantages afforded by SWIR are continuing to be realized and are influencing the next generation of both emitter and sensor innovation. Colloidal Quantum Dot (CQD®) SWIR sensors, pioneered by SWIR VISION SYSTEMS, deliver SWIR sensing capabilities at a cost per pixel below industry norms by virtue of a patented CQD semiconductor technology. CQD image sensing technology leverages standard CMOS design with quantum dot deposition to achieve the world's highest resolution SWIR imaging camera. At SWIR VISION SYSTEMS, we are applying our unique CQD technology and production methods to advance the existing state of the art in laser technology as well as to bring about new and exciting laser-based innovations across multiple markets.

SWIR Lasers

Various applications have long recognized the unique performance attributes of infrared (IR) lasers. Longer wavelength laser emission, for example, is heavily absorbed by the moisture content of the human eye, mitigating the risk of eye damage compared with visible lasers of similar output power. Due to SWIR radiation being invisible to humans, SWIR lasers can maintain a level of covert sensing that is not possible with other spectral regimes. More recently, a growing number of semiconductor SWIR lasers have been developed to address the demand for low-cost laser sources with wavelengths over 900 nm. Able to leverage cost synergies at scale, semiconductor laser technologies such as vertical cavity surface emitting laser (VCSELs) are being applied in higher volume applications such as telecom, motion sensing, biometrics, biomedical, and industrial automation. Solid state semiconductor lasers are progressing toward longer wavelengths well into the SWIR region with higher power density, better wall plug efficiency, and lower cost. In the following discussion, we will explore how SWIR VISION SYSTEMS ACUROS CQD cameras support these fundamental developments as well as bolster innovation in the most advanced laser applications.

Laser Imaging Basics

Laser based applications often require a precise understanding of the emitted optical energy and necessitate rigorous investigations into fundamental physics. Image sensors provide an otherwise invisible representation of SWIR laser emission and enable direct measurement of emission characteristics. Laser profiling is used to characterize emission properties and obtain critical diagnostic information. Both near-field and far-field laser profiles are useful in obtaining such information. Image sensors are used in combination with dedicated laser analysis software to facilitate these measurements. SWIR VISION SYSTEMS partners with DataRay Inc., a leading provider of complete laser profiling systems, to deliver turnkey laser profiling solutions.

Near-Field

In near-field laser profiling, a high-power lens is used to focus an actively illuminated light-emitting diode aperture onto a focal plane array (FPA) sensor. By imaging the actively illuminated aperture, the coupled electro-optical and thermal behavior associated with solid state laser emission can be observed. The setup depicted in Figure 1 serves to illustrate the basic concept. In practice, high power microscopes are commonly required to capture the necessary aperture detail.

Figure 1. CAD Depiction of a Near Field Imaging Setup Showing a SWIR VISION SYSTEMS Camera Equipped with a Lens and Focused on the Emitting Aperture of a Lasing Laser Diode

As shown in Figure 2 (left), the near-field emission profile of VCSEL arrays are often imaged to inspect yields as well as thermal gradients across the emitter die. In this scenario, the high dynamic range of the ACUROS camera is advantageous for capturing both peak intensity information as well as mean power distribution across the array. In another example, reliability engineers use micrographs of semiconductor lasers such as the VCSEL aperture shown in Figure 2 (right) to detect the formation of hairline cracks and other stress-induced defects during reliability and accelerated life testing. Near field images such as these can be critical in determining failure modes related to current crowding, hot spots, and other multiphysics phenomena. Here, the high-resolution and wide spectral range of ACUROS cameras set the standard for maximizing information content in near-field laser imaging.

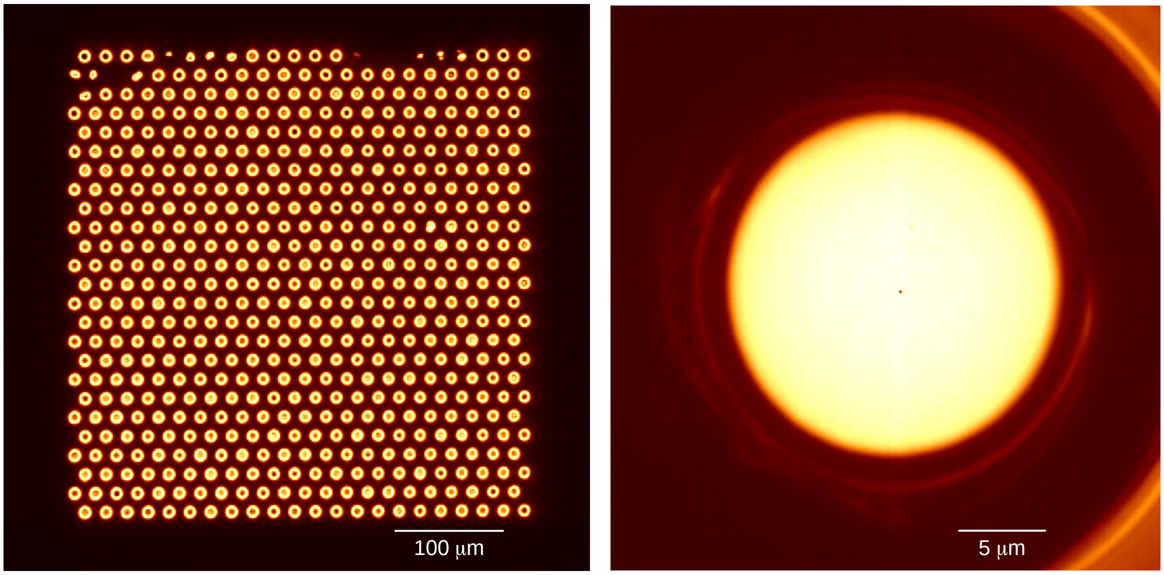

Figure 2. Near-field SWIR Image of an Illuminated 940 nm VCSEL Array (Left) and a Micrograph of a Single 940 nm Illuminated VCSEL Aperture (Right). Both Types of Imagery are Integral Tools for Assessing VCSEL Quality.

Far-Field

Laser profiling in the far-field is typically performed without a lens such that the fully developed wavefront of the laser emission is directly incident on the surface of the camera as depicted in Figure 3. Far-field laser profiles are used to measure laser properties such as optical power, divergence, mode shape, and polarization. Each of these measurements presents its own set of challenges and most cameras are not designed with these considerations in mind. The ACUROS family of SWIR cameras, however, is designed to address these challenges and is the ideal choice for far-field laser profiling.

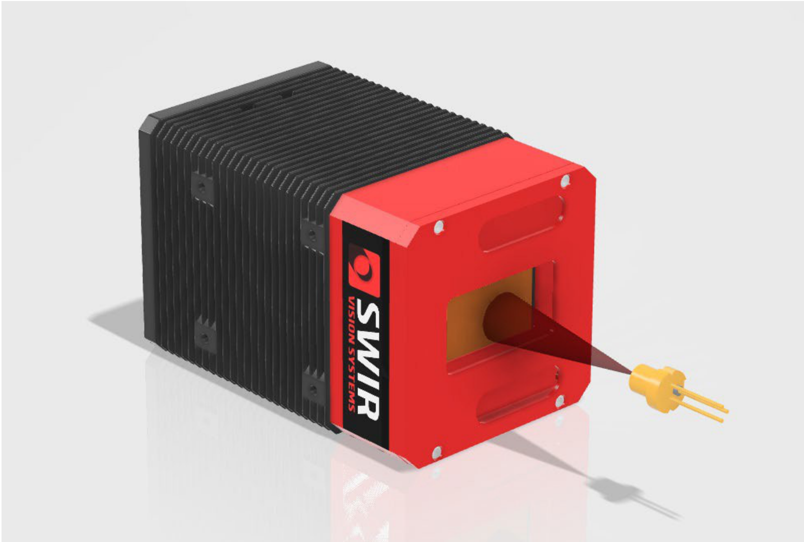

Figure 3. Far-field Imaging Using an ACUROS CQD Image Sensor. The 33 mm, 2.1 MP FPA is Ideal for Laser Profile Analysis. The Illustration Depicts the Custom Flange to Facilitate Filter Mounting While Minimizing Standoff Distance.

It is common for image sensors to be placed near the emitting aperture so that all the laser emission falls on the sensor's active area. Most camera designs include integrated lens attachments which prevent proximal access to the surface of the sensor array. ACUROS cameras, on the other hand, are equipped with a customizable front flange which minimizes laser-to-camera standoff distance.

Furthermore, the industry trend of smaller sensor formats can make it challenging to capture the full laser beam profile, especially for highly divergent semiconductor laser diodes. Full-HD (2.1 MP) ACUROS cameras are equipped with a 33.1 mm diagonal active sensor to ensure the entire beam profile is captured.

Finally, because analytical methods used for far-field beam profile analysis rely on simultaneous representation of both maximum and minimum laser beam features, dynamic range plays a critical role in far-field laser profiling applications. ACUROS SWIR and eSWIR cameras deliver 70 dB (14 bit mode) of dynamic range to deliver the industry leading solution for laser profiling accuracy and convenience.

Interference Fringing

Interference fringes are usually regarded as either a thing of beauty or a troublesome source of headaches. The distinguishing factor usually hinges on whether their presence is intentional or unanticipated. One potential source of fringing, generally overlooked and considered highly undesirable, is at the sensor surface where a cover glass is commonly used to protect the sensor from the environment. Optical interference resulting from nearly parallel reflective surfaces can wreak havoc on all sorts of laser imaging applications. Despite the use of wavelength dependent anti-reflective coatings that may have been applied to the cover glass to mitigate these effects, optical interference can still be problematic for laser imaging applications. The graphic in Figure 4 (left) illustrates the situation that commonly arises with image sensors that are not designed with laser imaging in mind. The red arrows represent (1) incident coherent laser emission encountering a partially reflective cover glass surface producing both (2) reflected and (3) transmitted propagation vectors. Path (2) becomes a potential source of interference when nearly parallel reflectors, located elsewhere in the setup, introduce phase shifted reflections back onto the image sensor plane. The transmitted path (3) becomes an even more likely source of interference fringing when multiple reflections between the sensor and the air-glass interface, depicted by propagation vectors (4) and (5), interfere constructively and destructively as demonstrated in the measured beam profile shown in Figure 5 (left).

SWIR VISION SYSTEMS designs and builds sensor packages from the die level up and utilizes a custom wedged glass solution to break the parallelism between the primary incident paths (1’) and (3’) as well as any externally reflecting paths that might occur. The wedge design not only provides essential protection but also imparts a sufficient degree of obliquity to virtually eliminate the interference fringing for the ACUROS laser series of cameras as measured in Figure 5 (right).

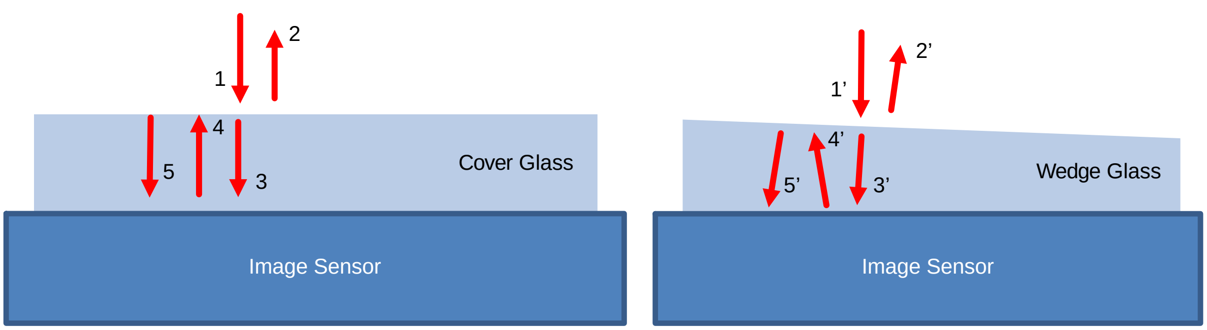

Figure 4. Representation of Interference Fringing from a Coherent Light Source in Imaging Glass. The Flat Glass Cover (Left) Creates Interference Due to Non-oblique Reflections, While the Wedged Glass Cover (Right) Attenuates Fringing Due to the Altered Angle of Incidence of the Light Source on the Image Sensor.

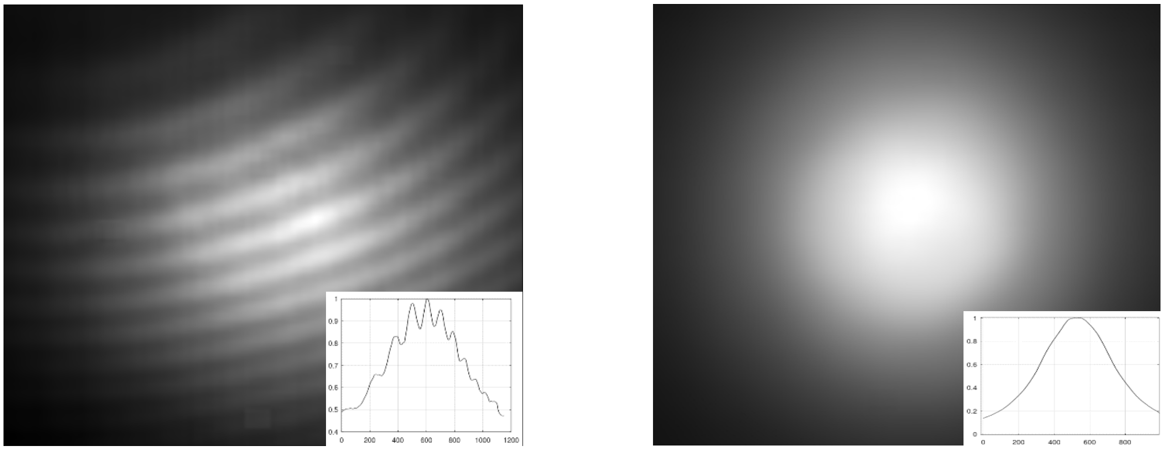

Figure 5. 1550 nm Far-field Laser Profile as Measured with a Conventional Flat Glass Cover (Left) and the ACUROS Wedged-glass Cover (Right). The Wedged Glass Cover Greatly Reduces the Effects of Fringing and Produces a More Accurate Representation of the Laser Beam Profile.

SWIR Laser Imaging in Practice

SWIR VISION SYSTEMS ACUROS Laser imaging sensors are engineered to suit a wide variety of laser imaging applications. With the highest resolution (Full HD, 2.1 MP) SWIR sensor on the market, available in a 28.8 mm x 16.2 mm (33.1 mm diagonal) active area 1920x1080 FPA form factor, the ACUROS Laser Line of image sensors deliver unmatched flexibility. In the following examples, we explore current and emerging imaging applications involving SWIR lasers to demonstrate where SWIR VISION SYSTEMS cameras are bolstering the state-of-the-art.

Medical

SWIR-band lasers are the gold standard in lithotripsy procedures for minimally invasive treatment of kidney stones. The lasers, generally near the 1900 nm absorption peak, create thermal expansion and ablate the kidney stones. The ablation results in significantly reduced particle size with the goal of allowing fragments to pass unimpeded.

The most common and mature technology is the Holmium: YAG solid-state laser operating at 2120 nm. Thulium fiber lasers (TFL) operating at 1908 nm or 1940 nm are being explored as a promising successor thanks to their lower cost profile, improved efficiency, and favorable beam profile as compared with Holmium lasers. With the prospect of TFLs as a disruptive technology in the lithotripsy segment, research is expanding and driving the need for higher-resolution laser beam profilers in the 1900 nm+ region, well beyond the spectral range of traditional InGaAs camera technology. The intensity profile of a 1900 nm TFL shown in Figure 6 was captured by a SWIR VISION SYSTEMS ACUROS eSWIR laser series camera demonstrating its unique capacity to support and promote the drive for safer and more efficient lithotripsy.

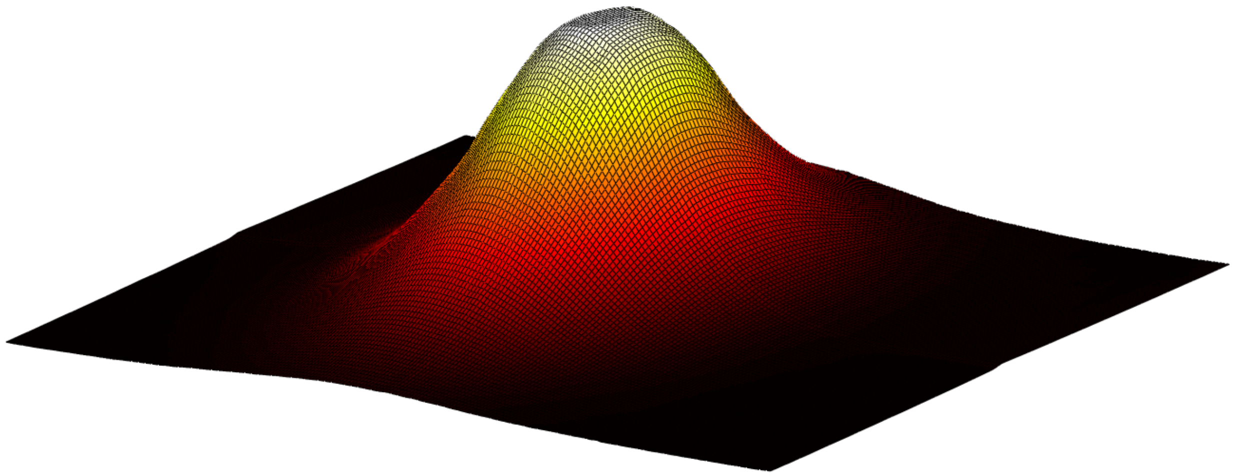

Figure 6. Intensity Map of a 1900 nm Thulium Fiber Laser as Captured by an ACUROS eSWIR Full HD (2.1 MP) Camera

In other medical applications, recent advances in medical imaging technology are taking advantage of reduced tissue scattering of SWIR wavelengths compared with NIR and VIS technologies where scattering has been shown to reduce image penetration depth. Absorption properties of constituent tissue materials including water, lipids, and collagen also tend to be more pronounced in the SWIR bands as compared to near-IR and visible regimes. Combined with the spatial profile as well as the temporal coherence properties of laser-based illumination, these optical interactions are the basis of ongoing investigations into the feasibility of SWIR based imaging for non-invasive blood glucose monitoring, various forms of cancer detection, and arteriosclerosis diagnostics [4, 5]. Hyperspectral medical imaging is yet another example of cutting-edge technology where SWIR based laser imaging is enabling exciting new capabilities in both diagnostics as well as on the operating table [6]. The unprecedented spectral range of ACUROS eSWIR cameras enables both tissue imaging and hyperspectral imaging applications to take full advantage of the SWIR spectrum. When combined with its unprecedented resolution and high SNR, ACUROS cameras are the ideal sensing platform for these exciting new biomedical imaging applications.

Military and Security

SWIR laser imaging plays a vital role in defense and security where covert sensing modalities are desirable. These applications include covert illumination for enhanced visibility, long range targeting/identification, and various forms of concealed communications. One example where SWIR sensing offers vital intelligence is in long range sensing. Atmospheric transmissions models predict, and real-world demonstrations validate, that longer SWIR wavelengths propagate more readily through haze and other harsh atmospheric conditions thanks to reduced scattering. In the dense surface layers of the atmosphere where most imaging applications occur, long range imaging is especially challenged by Mie and Rayleigh scattering, the latter of which scales inversely with the fourth power of wavelength [7]. Not only do SWIR based image sensors provide clearer imagery as a result of these atmospheric effects, SWIR lasers can be detected with greater accuracy and range providing enhanced modes of operation. A demonstration of ACUROS cameras for laser ranging application was recently carried out in conjunction with the US Military showing detection of a portable 1550 nm pulsed laser source beyond 2 km.

Figure 7. 1550 nm Laser Ranging in Full Sunlight at 1 km and 2 km Target Distances Using an ACUROS SWIR Camera

Time-of-Flight Depth Sensing

Time-of-flight (ToF) measurement using laser sources started to emerge in the early 2000's as semiconductor technology began to achieve the requisite processing speeds. More recently, consumer electronic devices have brought facial ID, autonomous driving, and other lidar based capabilities to the masses. One characteristic of these commercial facing applications is the need for eye-safe laser solutions which can address the range, field of view, and power requirements for a given application. SWIR wavelengths offer an important advantage over lower NIR wavelengths as they are inherently more eye safe. Furthermore, the same scattering properties discussed above play favorably into the range performance of SWIR based ToF systems especially in degraded environments. As ToF systems continue exploring the benefits of higher wavelength emitters, SWIR based cameras are becoming an increasingly effective tool in detecting and analyzing both emitted and reflected emission fields. ACUROS CQD camera technology has demonstrated value facilitating these efforts not only as a diagnostic tool for this spectral range of interest, but also as an enabler of new sensing architectures.

Summary

SWIR VISION SYSTEMS designs, builds, and sells a line of proprietary CQD cameras that have been tailored for laser-based imaging applications. Thanks to their unique characteristics such as a large sensor active area, specialized mounting solutions, high Dynamic Range, and fringeless imaging, ACUROS cameras are the preferred choice for any SWIR laser imaging application. Not only are ACUROS cameras opening doors for new applications in the eSWIR regions beyond 1.7 μm, but ACUROS laser series cameras are also playing a key role in enabling fundamentally new laser technologies.

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