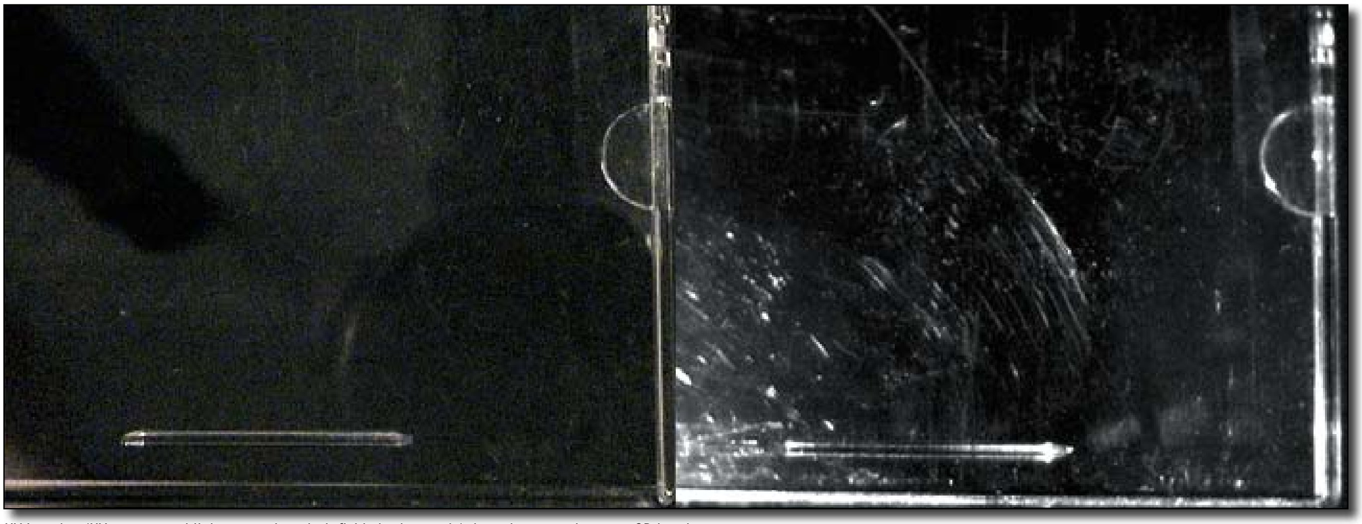
By Austin Richards, Ph.D.

Digital Reflected-Ultraviolet Imaging



UV Imaging (UV camera and light source in a dark-field viewing mode) detecting scratches on a CD jewel case.

- UV sensors, optics, illumination
- Reflected vs. fluorescence UV imaging
- UV Bands
- Mating system to application

Digital reflected-ultraviolet imaging has long been a specialized area of imaging technology that has only found its way into a rather limited number of applications, in spite of the fact that film-based reflected-UV photography has been around for over a century. This is due in part to the characteristics of electronic imaging devices: CCDs and CMOS arrays generally have a greatly reduced sensitivity to UV light relative to visible and near-infrared. It is critical that these undesirable wavebands be removed to get pure reflected-UV images, while still preserving the UV sensitivity of the system.

There is also a great deal of confusion about the difference between reflected-UV imaging and UV-fluorescence imaging. Many people think that the term "UV imaging" refers to the latter. In fact, reflected-UV and UV-fluorescence imaging are different techniques that see different things in a scene.

UV imaging in sunlight showing the application of fresh paint that was undetectable to the eye.

UV-fluorescence imaging starts with a UV excitation source that stimulates fluorescence of a material, that is, the re-emission of light at a longer wavelength. The fluorescence signal is often visible light that can be imaged with a conventional camera. The classic example of this is the forensics investigator that looks at a crime scene through yellow or orange filter glasses while illuminating a crime scene with a black light. Many types of trace evidence can be found in this manner, provided that the ambient light background is sufficiently reduced first. In contrast, reflected-UV imaging begins with a UV light source, and ends with the imaging of reflected UV light at the same wavelength by a special UV camera. In the past, this type of photography was done with standard black-and-white film, which sees UV light quite well.

Unfortunately, this method suffers from serious limitations related to composition, exposure control and focus. These limitations stem from the visible-light opacity of the UV pass filter combined with the inability of the eye to see UV light through the viewfinder, as well as the fact that light meters (whether external or in cameras) are not designed to measure UV light levels.

These difficulties, combined with a dearth of widely-available information about the proper techniques, have prevented film-based UV imaging from becoming as widespread as it might have otherwise. Digital reflected-UV imaging overcomes all of the limitations of film (albeit with a lower resolution for the time being), and now it stands poised to take off just as digital infrared imaging did ten years ago. The drivers are the availability of low-cost imaging solutions, the emergence of new and interesting applications and the rapidly improving family of high-power UV LEDs and lasers that provide pure, narrow-band UV illumination. As with infrared imaging technology, applications for UV imaging are extraordinarily diverse, and span a wide variety of disciplines, including forensics, laser technology, dermatology, biological research, art conservation and defense.

ULTRAVIOLET WAVEBANDS

The ultraviolet spectrum is divided into various sub-bands, with the most common convention dividing the region of the spectrum between 250 and 400nm (the near-UV band) into the A, B and C bands. In this convention, the A band is between 360 and 400nm, the B between 320 and 360nm, and the C between 250 and 320nm. UV below 250nm is sometimes called the deep-UV band. Below 100nm, UV light is very heavily absorbed by air, and experiments done in this band must be conducted in vacuo, leading to the name vacuum ultraviolet or VUV. The A, B and C bands are of practical interest for scientific and industrial imaging, since they are quite a bit easier to generate and detect than shorter wavelengths. UV-C radiation from the sun is heavily absorbed by the ozone layer, and any UV-C light encountered at sea level almost always comes from a man-made source.

Special cameras can detect the low levels of UV-C generated by corona discharge from high voltage machinery, as well as rocket plumes, muzzle flashes, and invisible flames. These cameras are based on image intensifiers with special UV photocathodes, and highly-developed filters to reduce the very substantial backgrounds to acceptable levels.

A new class of gallium nitride (GaN) photovoltaic detectors has been developed in recent years, primarily for defense applications, though these devices have not yet been developed into commercial cameras. Some of these GaN devices called solar-blind, because they have such high bandgap energies that they are naturally insensitive to visible and infrared light, and therefore do not require filters.

UV IMAGING SENSORS

As interest in digital reflected-UV imaging has grown, a small number of camera manufacturers and lens designers have specifically addressed the demands of this market and have produced off-the-shelf UV cameras based on silicon CCDs. UV sensitivity is often overlooked by CCD and CMOS camera manufacturers, who usually publish spectral response curves for their sensors that stop short at 400nm, the edge of human vision and the beginning of the near-UV region of the spectrum. This omission has sometimes made it difficult for scientists and engineers to select a suitable camera for reflected-UV imaging applications. In fact, many commercial visible-light CCD and CMOS cameras have UV-blocking layers incorporated into the optical path to prevent undesirable chromatic aberrations in the image, making them virtually useless for UV imaging.

Most of the emerging breed of UV-specific cameras are based on thinned CCD arrays, and are packaged for the machine-vision and industrial inspection market. The thinning process removes silicon material that prevents UV radiation from reaching the active layer in the detectors. This thinning process shortens the cut-on wavelength of the sensor down as low as ~200nm. Some newer CCDs are being built with ITO (indium tin oxide) instead of polysilicon gates. The ITO material is more transparent in the near-UV band, and allows shorter wavelengths of light to be detected as with thinning, but with a lower manufacturing cost.

As mentioned earlier, silicon CCD cameras are more sensitive in the visible and near-infrared bands than in the UV band, even with thinning, and the UV imaging system designer must carefully control the spectrum of light that reaches the sensor. Camera filters which pass near-UV light while also blocking visible and near-infrared are always required, unless the illumination itself is purely ultraviolet.

Yet another method for enhancing a silicon sensor's UV response is a waveshifting coating such as Metachrome. These fluorescent materials are applied directly onto the CCD surface during manufacture. UV-A light that would normally be absorbed in the silicon before generating carriers are instead converted to visible light, which is then easily detected by the CCD.

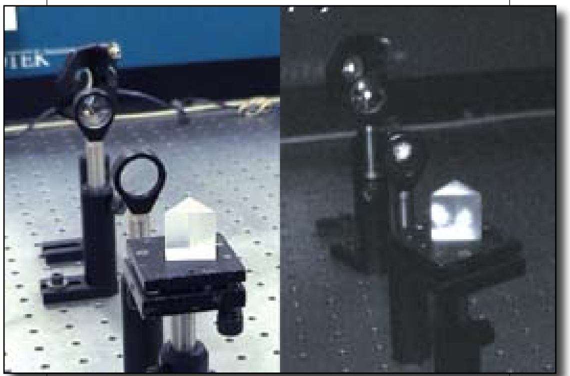
Ultraviolet image converters and image intensifiers are also commercially available, and are especially useful when the UV signal level is very low. These devices convert ultraviolet photons into electrons using an electrically-charged photocathode on the front of an evacuated image tube. The photoelectrons are converted to visible light via a green phosphor on the tube's anode, and can then be directly viewed by the operator. Relay lenses can be used to re-image the viewing screen onto a CCD or CMOS camera for applications demanding a video signal.

OPTICS AND SOURCES

A wavelength of interest in UV imaging is 310nm, the point at which standard optical glass, such as BK-7, starts to become opaque. Imaging below the glass cut-off wavelength requires special lenses made with optical materials that have good UV transmission. These include difficult-to-form materials such as fused silica (quartz) and calcium fluoride. For these reasons, UV camera lenses are typically quite expensive compared to standard visible-light camera lenses. Fortunately, some conventional color video camera lenses designed for visible-light systems have decent transmission in the UV band down to about 320nm, although it is largely a matter of trial and error to determine which lenses will work. Typically, less expensive color video lenses work better, especially if they lack the AR coatings which are designed to reject undesirable UV and near-IR light.

UV illumination is often quite weak in indoor situations, requiring that active illumination be used. Traditional UV sources include both high and low pressure mercury discharge lamps which generate UV light at 365nm and 254nm respectively. These UV light sources are not pure ultraviolet in nature, since the lamp's spectrum is broadband, and the colored-glass filters used to reduce visible and infrared light tend to leak red light, to which silicon detectors are quite sensitive. These days, a number of manufacturers (such as Nichia) are producing LEDs in the 365-400nm waveband. These LEDs are typically very spectrally pure, with FWHM values of ~10nm and have power levels up to 100mW. They are now making their way into lighting modules for integration into machine-vision systems.

Outdoor imaging in the UV-A and UV-B bands benefits from a generous flux of photons in these ultraviolet bands from the sun, even in cloudy conditions. Since the color temperature of the sun is quite high relative to tungsten lighting, the camera system is not overwhelmed by the very high ratio of infrared and visible light to UV, as is the case with conventional indoor lighting. For example, ordinary indoor lighting operates at a color temperature of 2800 K. There are about 40 times as many photons emitted by this light source at 720nm as there are at 360nm. In bright sunny conditions, the color temperature of the sun is roughly 5600 K at sea level. That ratio of 720nm light to 360nm light changes to two to one, making it easier to image in the UV band while simultaneously rejecting longer wavelengths of light that contaminate the UV image.



Imaging a 355nm frequency-tripled YAG laser scattered off optical components.

UV IMAGING APPLICATIONS

As with infrared imaging, the applications for reflected-UV imaging are very diverse. As more and more UV cameras become available to commercial customers, the list of practical applications will certainly grow longer. One way to look at ultraviolet imaging is that it is all about absorption. Many common materials (especially those based on organic molecules) strongly absorb near-UV light due to electronic transitions. Changes or modifications to the surface of the material can affect this UV absorption, making the changes easier to detect. In contrast, near-infrared imaging applications are often all about transmission. Many materials that are opaque in the visible band are actually quite transparent in the near-infrared band (generally defined as being between 750 and 1100nm). These materials include ink, paint, fabric dye, silicon wafers, thin paper and plastic. Many practical near-IR applications thus require that something be rendered transparent. The near-infrared and near-UV bands seem to be complementary in nature in terms of imaging applications. Some of the most interesting applications for reflected-UV imaging:

- Imaging surface texture not apparent to visible-light imaging
- Detecting changes in painted or coated surfaces due to variances in UV reflectance
- Imaging UV lasers, LEDs and other ultraviolet light sources
- Detecting sun damage, bite marks and bruises on skin
- Evaluating the efficacy of sunblock and the uniformity of its application to skin
- Detecting trace evidence not apparent to fluorescence imaging, infrared or visible-light
- Detecting both natural and manmade white camouflage in snowy conditions
- Visualizing markings on flowers and butterflies that are only visible in the near-UV band
- Visualizing repairs, cracks and damage to teeth

CONCLUSION

This is a very exciting time for reflected-ultraviolet imaging technology. The availability of commercial digital ultraviolet cameras, combined with off-the-shelf quartz lenses and high-power, solid-state UV light sources are making it possible to implement robust reflected-UV imaging solutions at very reasonable costs. I predict that we will see increasing interest and many new applications as greater numbers of these cameras get into the hands of industrial, military and R&D users. ***AI***

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