Long Term Stability and Reliability of Permanently Installed On-Line UV Sensors

Kyle Bostian
Electronic Instrumentation and Technology, Inc.

Abstract

UV sensors are typically very sensitive to aging and solarization effects of the harsh environment in which they are used. Minimizing the long term effects of UV on a sensor/optics is extremely challenging, especially with on-line installed sensors used for continuous monitoring on a 24/7 basis. This paper describes a patented method of reducing the effects of aging and solarization to a minimal amount so a user can monitor and control a curing process with a robust, stable and consistent sensor. This paper reviews the impact of radiation (UV, Visible, IR) on the optical components (photodiodes, optical filters) in a sensor and presents the test data showing sensor performance over thousands of hours of operation with little or no deterioration.

Construction of Optical Sensors

Sensors for the measurement of optical radiation levels typically consist of three elements:

- A *detector* converts optical energy incident on the sensor to electrical energy, typically in the form of an electric current.
- An *optical filter* selects wavelengths of interest from the incident light to be transferred to the detector.
- *Input Optics* can serve both to protect the other elements of the sensor, and to achieve a desired spatial response for the sensor. For example, a diffuse optical element is employed to achieve cosine response in the sensor.

Every sensor system, at a minimum, has a detector. Optical filters are omitted in applications where the detector response and the band of interest are the same, or when it is assumed that the level of radiation in the band of interest will be well-correlated with a broader band. Other input optics are omitted in applications where spatial response does not require additional control, the other elements do not require mechanical protection, or where their cost would be prohibitive.
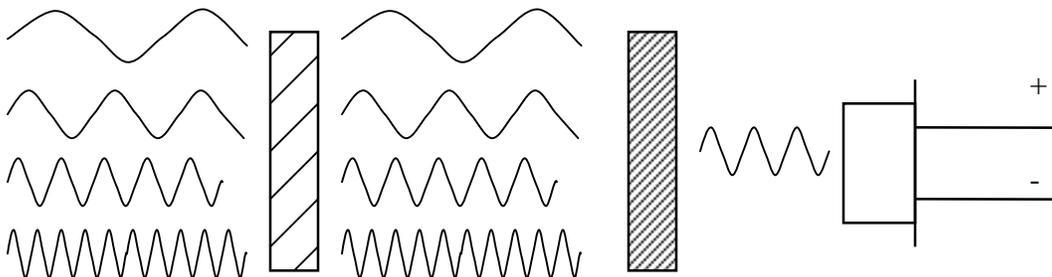
Figure 1: Elements of an Optical Sensor - Input, Filter, and Detector.

A wide variety of sensor systems have been developed for the monitoring of the output of UV systems. For many applications, acceptable results have been obtained by the application of standard electro-optical design practices. The degradation of optical materials was a known problem, and solutions tended to focus on keeping the sensor protected from the environment, through either remote viewing of the system output, or through the use of a shutter to sample system output.

Detectors
In the ultraviolet region of the electromagnetic spectrum, there is a wide range of available detectors. Perhaps the most widely deployed detector in the ultraviolet is the Cadmium Sulfide photoresistor, which finds wide use in cameras and furnace flame detectors, due to its ease of use and low cost. Its slow response to changing light levels, though, limits its application in sensors used for industrial control.

Faster response times are available from photodiodes. A photodiode consists of a junction between p-type semiconductor material and n-type semiconductor material. The p type semiconductor material has an excess of holes; the n type material has an excess of electrons. At their junction, the excess holes and electrons interact through recombination, producing ions on each side of the junction. Negative ions are present on the p side of the junction, and positive ions are present on the n side of the junction. This creates an inherent electric field in the junction.

When a photon with sufficient energy (i.e. of the correct wavelength range) is incident upon and becomes absorbed by the semiconductor, a mobile electron and an electron hole are generated.   The electric field present in the junction acts upon the electron, creating a photocurrent. This current will be proportional to the irradiance at the detector.

The range of wavelengths to which the photodiode will respond is related to the difference in electron energy between the valence and conduction bands, or bandgap, of the semiconductor material. Each semiconductor material has an inherent bandgap, and many semiconductor materials have a bandgap corresponding to ultraviolet photons. These include Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Gallium Nitride (GaN), and Silicon Carbide (SiC.) The most common detector, though, is a conventional silicon photodiode. Its bandgap corresponds to the 190nm – 1100nm wavelength range.
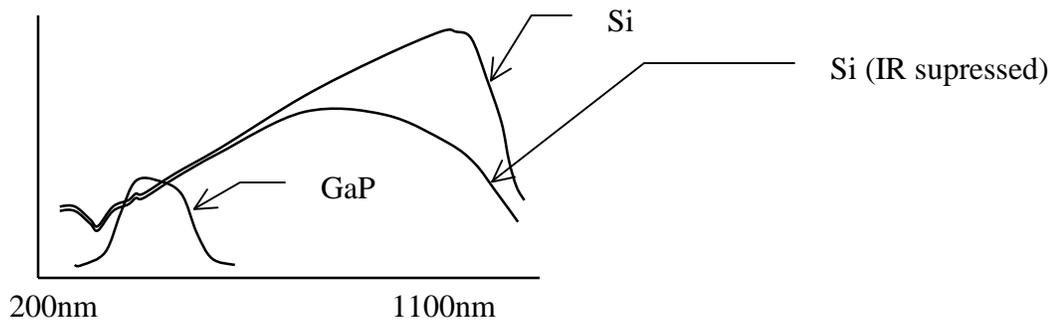
Figure 2. Spectral Response of Common UV Detectors

Optical Filters
Optical filters applied in ultraviolet sensors selectively transmit optical radiation using absorption, thin-film effects, or both.

In absorption, photons are destroyed when they interact with atoms in a material, causing transitions between electronic energy levels. The wavelength range of radiation that is absorbed is affected by the available transitions in state between energy levels in the atoms in that material.

Thin film effects are best understood when considering the optical radiation as a wave rather than a particle. Thin film effects occur when thin layers of alternating high and low index materials are in the path of radiation. Depending on the indices of refraction of the layers and their thickness, waves traveling in the incident direction will either pass through the film, or be cancelled by antiphase waves traveling away from the incident direction. It is not uncommon for an optical filter to apply both principles, where a thin film complex is coated on an absorptive substrate.   These filters are also commonly called interference filters.

The Measurement Environment
There are several common environmental factors which need to be considered in sensor applications.

Ultraviolet Radiation
At a minimum, each sensor application involves exposure to the very ultraviolet radiation that the user wishes to measure. The irradiance levels at the sensor location can vary greatly, from the order of watts per centimeter squared of irradiance, down to tens of microwatts of irradiance. Even at the low end of this range, the ionizing effect of ultraviolet radiation can have a drastic impact on materials over long periods of time.

Temperature
Many UV sensors are exposed to elevated temperatures. Germicidal systems typically have small temperature increases – perhaps 5°C to 10°C above ambient – but in some processing applications, the ambient temperature may also be high, up to 100°C. Higher power lamp systems, typically used for curing, have much higher rises above the ambient, with operating temperatures approaching 130°C.

Other Optical Radiation
Most sources of UV radiation also produce visible and infrared radiation. The absorption of this radiation by the sensor typically results in the heating of the sensor, causing similar effects to those of elevated temperatures.

Humidity
UV sensors are applied in extreme humidity environments. For example, in a cleanroom the humidity may be expected to be exceptionally low; in a food processing or water treatment application, the humidity may be very high, to the point that condensation may occur.

Vibration
UV systems typically require a large volume of cooling air, and are typically fitted with large blowers to provide such air. These blowers are a source of mechanical vibration, which can affect the positional stability of UV sensors, affecting end user measurements. In systems with a conveyor, the conveyor system is another potential source of vibration.

Electrostatic Discharge
The high airflow in a UV system can cause the accumulation of electrostatic charge. If these charges are discharged through a sensor or its monitoring electronics, damage to the measurement system will occur. An aggravating factor here, is that some applications require the generation of electrostatic charge, which can be especially harmful to the electronics.

Techniques for the protection of electronic sensors and optical systems from the effects of temperature, humidity, mechanical vibration, and electrostatic discharge are fairly well known; this paper will focus on the protection of the sensor from the effects of optical radiation.

Effects on Sensor Materials

The design of a robust sensor begins with an understanding of the underlying effects of optical radiation on the sensor. High levels of optical radiation affect each portion of the sensor in different ways.

Detector
In addition to the photocurrent produced by a detector, all photodiodes produce a dark current. The dark current is a source of error in a continuous UV sensor system, since it simply adds to the photocurrent to become part of the measured signal. Dark current is caused by the promotion of electronics from the valence band to the conduction band by thermal excitation. Ionization from ultraviolet radiation damage can change the relationship between the valence and conduction bands and cause an increase in dark current.

Researchers at the Queen's University of Belfast have described and measured the effect of ultraviolet radiation on the dark current of a silicon photodiode(Al-Wazzan 166). In their case, they studied an array, but the breakdown mechanism extends to the case of simple point detectors. In their experiment, a photodiode was continuously irradiated with radiation of wavelength 253.7nm (which is in the UVC range) at an irradiance of 10.5 uW/cm2. They observed that the dark current from the detectors increased linearly with the exposure time. In 8 hours of exposure at this irradiance level, the dark current of the photodiodes increased 10.2%.

In an undamaged photodiode, the dark current increases as temperature increases. The Belfast results show that the dark current's dependence on temperature increased with this damage.

Researchers at the National Institute for Standards and Technology (NIST) have studied the effects of long term exposure to ultraviolet radiation on the responsivity of the detector.(2) The responsivity of the detector is the relationship between the device output current and the optical radiation incident upon it, and is therefore obviously an important parameter of the device.

The NIST test exposed various silicon and compound semiconductor detectors to radiation at 193nm, 157nm, and 135nm radiation. While the effects at the shorter vacuum wavelengths were more severe, the results at 193nm are apropos to the design of UV sensors, since this wavelength will transmit over reasonable distances in air. The effect on responsivity was dependent on the type of detector. GaN detectors degraded linearly with exposure. Si detectors were generally stable with exposure to a point, at which point the response would start to degrade linearly. Other detectors, such as PtSi or nitrided silicon, would increase in response with exposure, only to reach a critical point after a long exposure period.

The NIST paper identifies the radiation-induced formation of traps, which block photocurrents, as the likely source of the responsivity phenomenon. However, it goes on to state that little is known about the mechanism, and that this is simply postulated.

Optical Filters
A common material in optical filters is colored filter glass. These are glasses of various types, which have had additives (generally metals and metal oxides) introduced during their manufacture. Colored filter glasses achieve filtering through the bulk effect of absorption but also are used as substrates in thin film systems.

Colored filter glasses exhibit a photodarkening effect, by which their transmission is reduced evenly across their transmission spectra after exposure to optical radiation (Yanagawa 371.) Ionic impurities that are present in the glass form crystals upon being excited from optical radiation. These crystals absorb optical radiation across a wide band.

Optical Elements
There are several phenomena by which ultraviolet radiation can cause degradation in general optical elements. It should be noted that the mechanisms presented here will generally apply to both optical filters and the entrance windows of detectors.

One of these is the polymerization of hydrocarbon contaminants on the surface of optical elements (Floyd 1459.). The resultant polymer blocks some of the incident radiation, decreasing the system output signal. It was shown that, under continuous exposure, the effect could be reasonably measured and modeled. The effect was consistent across two windows of different construction, reinforcing the theory that the degradation was caused by a surface contaminant, and not due to a change in bulk properties.

A second mechanism is Solarization. Solarization is perhaps the most widely known effect of optical radiation on glass. Solarization was reported as early as 1930. (Stockbarger 455.) Solarization is the coloration that occurs in optical glasses, when ultraviolet radiation causes ionic contaminants in the glass to reach a more positive state.(Gliemeroth 67.) Common contaminants are cerium, iron, manganese, europium, arsenic, and antimony. The stability of the ions in this more positive state is difficult to predict.

The effect of solarization can be reversed at higher temperatures, and the effects of solarization can be very different depending on the composition of the glass and its temperature. This reversal effect has been clearly shown in BK7 (Stolz 44.)

Principles for Design

The various physical effects give rise to two principles which can guide the development of sensors for continuous monitoring of UV systems:

- Minimize Contamination. The UV sensor should be constructed from materials that provide the lowest possible level of contaminants, for it is contaminants that are affected by ultraviolet radiation, and in turn cause degradation of the materials.
- Minimize Optical Radiation. The UV sensor should be designed to operate with the lowest possible level of optical radiation incident on its component parts, as the damage mechanisms are all proportional to the level of radiation incident on the component.

A Solarization Resistant Sensor

A sensor design based upon these principles is described by May.(May 1.)

The sensor is housed in an optics block, which has a large cavity to contain the various optical components, and a smaller cavity, which serves as an entrance port for the sensor. The length of the entrance port limits the field of view of the sensor. A limited field of view is not always a desirable characteristic in a sensor, but for this sensor it is an advantage. The narrow field of view allows the user to point the sensor at a portion of the reflector system on the UV source. In this way, the output signal will be sensitive to both decline in output of the original UV source and to contamination of the reflector surfaces. If extraneous radiation was accepted by the sensor, it would be difficult to assure that the sensor could detect the reflector contamination, since the direct radiation from the bulb could overwhelm the smaller reflected signal.

After entering the optical port, radiation is incident on an optical window. The optical window is constructed from a fused silica that is high in purity and therefore resistant to solarization. The fused silica material is available from several sources, but it is most widely known by the trade name used by Heraeus for their product: Suprasil.

The optical window is diffuse on one side. This causes the radiation incident on the window to be diffused out over a 180 degree angle

The next element is a very small aperture. Although the aperture is near the window, it subtends only a small angle of the total output of the first window, causing the amount of optical radiation to be greatly attenuated.

The optical radiation then passes though another diffused window. Just as the first window, this window distributes the incident radiation over a 180 degree angle.

A spacer follows this window. At the far side of the spacer, there is an optical filter. The combination of the diffuse surface of the window and the distance due to the spacer causes the angle subtended by the filter to be a fraction of 180 degrees. This causes another stage of attenuation, albeit not as great of attenuation as the first stage.

The optical filter allows only the band to be measured to be passed. The optical filter elements vary according to the UV band to be measured, but they are selected to be resistant to the effects of elevated temperature. Also, although the cavity is reasonably well protected from the outside environment, the filter materials are selected to be stable under long term exposure to humidity.

The final element in the sensor is the photodiode. The photodiode is selected to be resistant to solarization effects, but the majority of its protection comes from the optical attenuation in the other elements.

Signal Processing

The output from the sensor is transmitted to a signal conditioning device for further processing. The first element in this device is generally a transimpedance amplifier, which converts the small current output signal from the sensor to a voltage signal.

In the conventional approach to signal processing, one desires to couple the largest possible signal into a device. The sources of noise in the circuit, related to the signal processing electronics and the inherent characteristics of the detector, remain the same they would be if full scale signals were coupled into these devices. Achieving a full scale signal maximizes the signal-to-noise ratio. In this case, though, signal is intentionally discarded in order to provide long term stability.

In order to keep the signal-to-noise ratio at an acceptable level, the transimpedance circuit must be carefully designed. Noise analysis of the transimpedance circuit, and the relationship between noise performance and other circuit parameters, are presented in a number of sources. (Steffes)

Long Term Testing

The sensor was subjected to a long term stability test, in order to prove out its suitability for continuous monitoring of UV systems.

Two test sensors were prepared. Measurements were made to establish a baseline condition for the sensors. The sensor output was measured by measuring output current in front of a light source with a known radiance level.   Additionally, the optical filter in the sensor was characterized using a spectrophotometer. (Shimadzu UV-260)

The sensors were then taken to a facility, which had several 600 watt-per-inch or wpi (240 watts per centimeter or wpcm) , microwave excited, medium pressure mercury arc lamps in continuous, 24 hour per day operation. The sensors were mounted in a position near the elliptical reflector. The optical port was aligned directly with the bulb. This is a severe test; as noted earlier, there are advantages to directing the sensor to reflected energy; continuous monitoring *by direct view of the lamp* is not always desired, or necessary.

The sensors were left in this facility, and serially removed from the system. One sensor was removed at 4100 hours of run time, and the second sensor was removed at 6752 hours of run time.

The output and filter characterization measurements were repeated after the sensors were tested.

<div align="center">Results</div>

Table 1 shows the output current measurements before and after the long term test for each sensor.

	Sensor 1	Sensor 2
Pre-Test		
Output Current (uA)	1.18	1.28
Irradiance (mW/cm^2)	184.4	184.4
Resposivity (A/W)	6.399E-06	6.941E-06
Hours in Service	4100	6752
Post-Test		
Output Current (uA)	1.11	1.21
Irradiance (mW/cm^2)	178.1	178.1
Resposivity (A/W)	6.232E-06	6.794E-06
Change in Responsivity	-2.60%	-2.12%
Uncertainty	±2.5%	±2.5%

<div align="center">*Table 1. Sensor Test Data*</div>

Figure 3 shows a plot of the spectral response of the filters in each sensor, before and after the test.
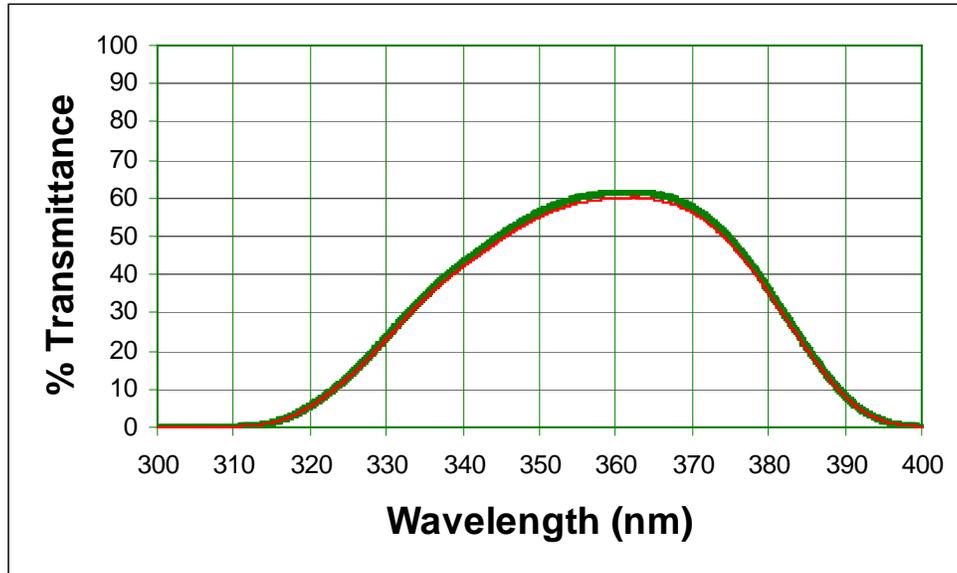
Figure 3. Spectral Response of Bandpass Filter from Sensor1, before and after testing. The peak transmittance of the filter in Sensor 1 decreased by 2.45%; the peak transmittance of the filter from Sensor 2 decreased by 1.95%.

Discussion of Results

A small decrease in output was observed on each sensor. The amount of the decrease was smaller than the uncertainty in measurement for each of the measurements made. Sensor #2 had a longer exposure than sensor #1, but had less loss in output. However, results between the two test methods were similar: sensor #1 had a larger change in both the responsivity and in the filter spectral response. A larger test would be required to state with any certainty that the change in filter response dominates the change in sensor output, but the construction of the sensor would be consistent with this observation. Since broad-band radiation is incident on the filter, but only narrow band radiation is incident on the detector, the energy absorbed by the detector is much smaller than the energy absorbed by the filter.

Enabled Applications

There are many applications which could benefit from continuous monitoring of extremely high power (500 wpi / 200 wpcm and up) UV systems, especially since the high line speeds typically associated with these systems translates into a high cost of scrap when product does not achieve cure.

Previous solutions to these measurement problems, although ingenious, suffered from drawbacks. One such example is a custom radiometer developed to measure the performance of curing systems for optical fiber. (Stowe 1987)

The system to be measured consisted of a microwave excited lamp system, with its bulb oriented in a vertical direction. An auxiliary elliptical reflector was placed on the output side of the lamp, so a full reflective ellipse was formed around a central area. At one

focus of this ellipse was the bulb; at the other focus of this ellipse was a quartz tube, which served as an envelope for a fiber that travels vertically through the housing.

The custom radiometer viewed the bulb from a port in the auxiliary reflector, so it monitored UV output through the quartz tube. The input optic for the radiometer was a quartz rod, which directs light from the point on the reflector to a point outside immediate area of the lamp.

At this point, a shutter was placed, to limit the exposure of the remaining elements of the system. Finally, there was a diffuser, filter, and detector as present in a conventional UV sensor.

The system worked well but there were two areas where the system could be simplified. The first is the need for the quartz probe, which, while extremely stable, is expensive, fragile, and prone to introduce errors if its tip is contaminated or if it is mechanically perturbed. The second is the need for a shutter; while the shutter provides for measurement at will, it makes continuous monitoring impractical.

The sensor described in this article is used to monitor curing systems in a curing configuration similar to the one described by Stowe. The sensor is installed at the port in the auxiliary reflector, and a cable is used to bring that signal out of the immediate area of the lamp and to a signal processing box. The sensor requires no shutter and provides a continuous, direct view of the lamp through the quartz envelope. Any mechanical perturbation of the cable from the reflector to the signal box is unlikely to affect the measurement. Also, a purge port is provided on the sensor. System air(filtered for moisture and oil) can be connected to the purge port, directing airflow out the optical port of the sensor which prevents contamination on the sensor's input optics.

Conclusion

The paradox of continuous UV measurement is that the very radiation one desires to measure can wreak havoc on all of the materials that make up the optical designer's toolbox. However, with careful design, it is possible to achieve continuous measurements by applying two simple principles – minimize the admission of optical radiation to the bare minimum, and select materials carefully with an eye toward reliability. The resulting sensors are stable over long exposures to high-powered UV systems and enable continuous UV measurements that were previously difficult, if not impossible.

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