UV LED Family

UV or not UV?

Abstract

UV or not UV? The potential risks of ultraviolet (UV) radiation are widely known however the positive effects of this radiation outweigh these risks. Over a century, mercury-based lamps have been the primary source of UV radiation mainly in the curing industry, with a peak emission of 254 nm and 365 nm. However, with reference to the Minamata Convention on Mercury, they will soon be phased out entirely and replaced with a more sustainable and greener energy light source: LED. It is apparent that LED technology is revolutionizing the lighting industry by offering energy savings, toxic-free qualities, longer lifetime, small footprints, narrower spectral bands, and low heat generation.

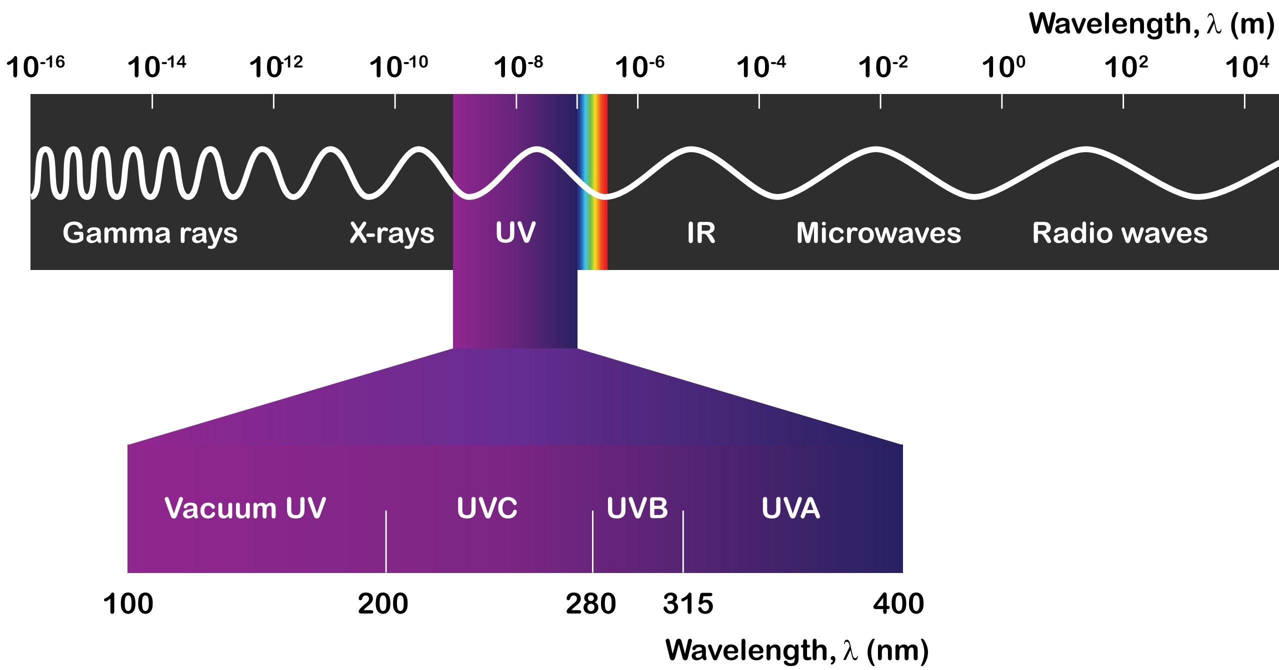
Unlike visible LEDs, UV LEDs have witnessed moderate adoption in recent years but have gained traction especially in the curing industry as significant improvements have been made. According to the Omdia Optoelectronics Components Report in 2020, the growth is estimated to continue from $162 million in 2019 to $553 million by 2025 at a forecast CAGR growth rate of 22.7% globally. This stems from the fact that UV LEDs can outperform and outlast Mercury lamps which eventually leads to reduction of cost while the efficiency and output consistency continue to improve. With the continuous evolution of UV LEDs, the potential of expanding into new and emerging applications such as purification, sterilization, horticulture, and medical phototherapy are being explored and evaluated. Hence, the future growth of UV LEDs are justifiable.

This article focuses mainly on UVA and some of its major applications, addressing the lesser known benefits of using UVA radiation as well as providing an insight of the high-power UVA LEDs offered by Broadcom ranging from 365 nm to 425 nm.

Introduction: Beyond the Spectrum

UV is defined as a form of radiation that is a part of the electromagnetic (EM) spectrum with wavelengths greater than 100 nm (X-rays) and shorter than 400 nm (visible light). The UV wavelength lies close to visible light but its wavelength is too short to be seen by the human eye. The shorter the wavelength, the higher energy the radiation gets. UV radiation is classified as the region of the electromagnetic spectrum that interacts with matter by excitation of molecules causing a chemical reaction which makes materials visible or "glow". UV can then be divided into three wavelength bands; UVA (315 to 400 nm), UVB (280 to 315 nm), and UVC (100 to 280 nm). UV radiation comes naturally from the sun and the rays that reach the surface of the earth comprise 95% UVA radiation and 5% UVB radiation while UVC radiation is completely blocked by the ozone layer of the Earth's atmosphere. UVA, also known as blacklight, has the highest depth of penetration and is considered to be the safest ray as it is closest to visible light while UVB or "burning ray", is usually associated with the development of sunburn and skin cancer. UVC is known as the germicidal wavelength which poses the highest risk to human health.

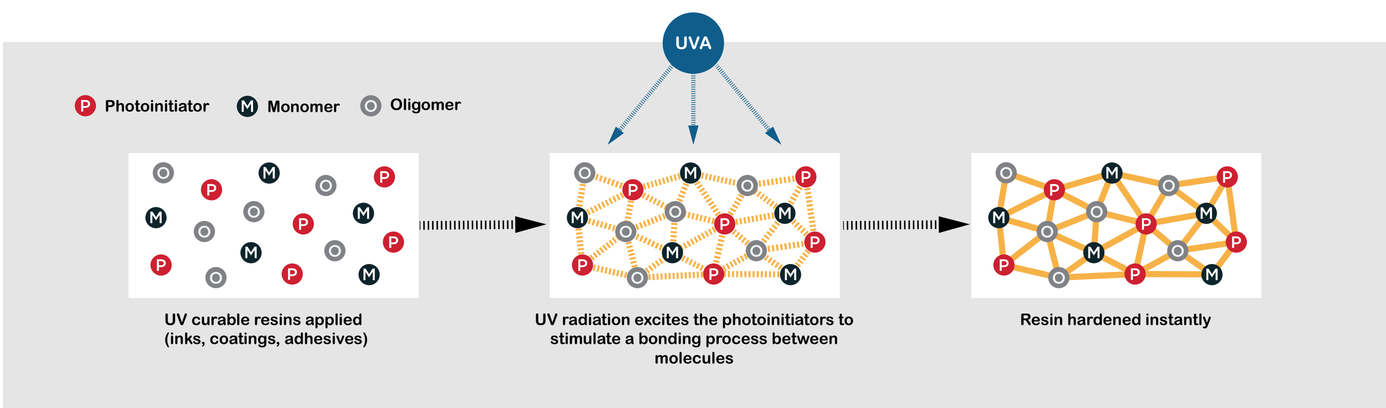
Figure 1: The Electromagnetic Spectrum—Wavelengths Definitions Based on ISO21348 Space Environment (Natural Artificial)



UV Curing

There are many applications within various industries currently exploiting the benefits of UV radiation—particularly UVA—for which different spectral bands and dosage levels are required for different purposes. One of the largest application sectors for UVA is UV curing which involves printing, bonding, coating, finishing, and assembling a variety of products. UV curing is described as a photopolymerization process that utilizes the UV photon energy to instantly transform liquid into solid forms (inks, coatings, adhesives, and other UV curable materials, as examples). Unlike evaporation or heat curing, UV radiation cures via direct polymerization at high speed where a photochemical reaction is initiated during UV absorption to form a crosslinked network of polymers (shown in Figure 2). The process offers an increase in speed of cure, with solvent-free and improved adhesion quality boosting production capacity and overall efficiency.

Figure 2: The UVA Radiation Curing Mechanism



Although mercury-based lamps have been dominating the industry, many have switched to LED technology mainly due to its compatibility with heat-sensitive substrates or components. Mercury lamps typically emit only 20% of UV light energy while the remaining energy is emitted as infrared (IR) and the heat generated by IR can cause unwanted curing or over-curing of certain materials. For UV LEDs, most energy is converted into light while a small amount of heat is dissipated out of the bottom of the LED package through the heat sink. Apart from that, spot curing on smaller or larger areas can also be achieved through secondary optics or narrow-angled LEDs which emit a more concentrated beam with higher light intensity. Spot curing is crucial in assemblies that require a higher precision control such as compact medical instruments and electronic components.

UV LED curing light systems often incorporate UVA wavelength ranges typically at 365 nm, 385 nm, and 395 nm compared to UVB and UVC due to its greater depth of penetration properties feasible for curing through thick pigments or layers which can be challenging to cure. The UV LED light systems can significantly affect physical properties of the UV curable resins such as hardness, opacity, and scratch resistance. To achieve an optimal cure, the UV curable resins must receive the proper amount of UV dosage, with the combination of time of exposure and light intensity at the specific wavelength that matches the optical characteristics of that material. A mismatch may result in weaker bonds or slower cure. Typical UV curable resin components consist of oligomers, monomers, and photoinitiators and many available in the market are optimized to function in the UVA range.

Sterilization/Disinfection

Sterilization and disinfection has been practiced by human society for thousands of years. The process is being carried out on food, water, air, and on objects and surfaces. Several disinfection methods such as chlorination, liquid chemicals disinfectants, dry heat, and UV exposure have been widely used to fight against harmful bacterias and microorganisms. Although these methods are proven effective, UV disinfection is considered more advantageous as it is a purely physical process and provides a chemical-free solution which eliminates the use of toxic chemicals and the formation of carcinogenic disinfection by-products (DBP). Solar Disinfection (SODIS)—one of the water treatment methods applied in low-income regions—is known to effectively eliminate waterborne microorganisms when they are simultaneously exposed to both UVA radiation from the sun and increased high temperature.

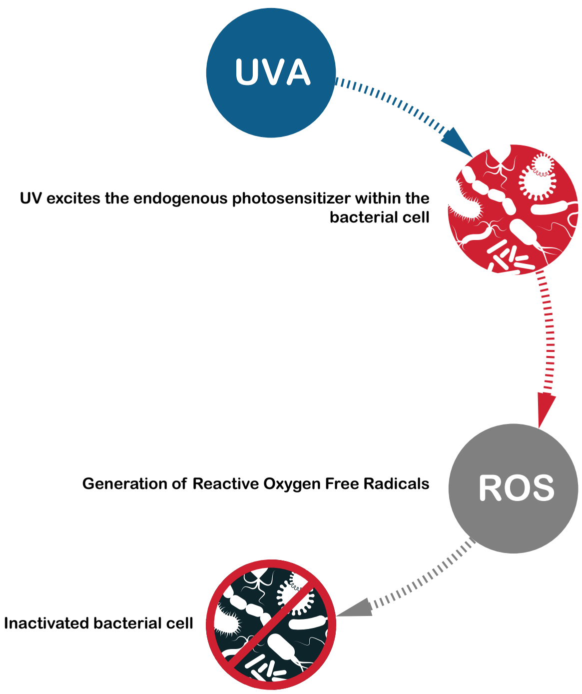
Today, the use of UV LEDs in disinfection lighting systems are becoming more and more widespread in industrial, commercial, and residential applications as they have developed into a viable solution to supersede conventional UV lamps. UV LEDs can provide an ideal disinfection system that is not only cost-effective, but without negative impact to the environment. Furthermore, with the recent outbreak of the COVID-19 pandemic, the demand has surged for a more reliable and effective disinfection system in terms of germicidal properties. UVC radiation particularly in the spectral region of 260 nm to 265 nm has a greater germicidal effectiveness compared to UVA but its associated safety hazards to humans as well as material degradation makes its implementations more complicated. According to IEC 62471:2006 on the photobiological safety of lamps and lamp systems, UVA radiation has no harmful effect on human skin or eyes at a controlled dosage. Moreover, it can also help to fight secondary infections. Several studies have shown that UVA radiation is able to deactivate pathogenic microorganisms such as E.coli, Staphylococcus aureus (MRSA), Candida auris, and so on.

Visible Light Disinfection

Visible light disinfection (VLD), as the name implies, operates in the visible or near-UVA light spectrum of 405 nm to provide a safer means of low-level disinfection. Considering 405 nm resides just outside of the UVA region in the electromagnetic spectrum, the disinfection mechanisms of both spectral bands are similar to some extent. When bacteria are exposed to 405 nm or UVA radiation, the endogenous photosensitizer porphyrins within the bacteria cell absorb the UV photons which then causes a photo-excitation leading to the generation of Reactive Oxygen Species (ROS) shown in Figure 3. While UVC kills cells by breaking their DNA strands, UVA causes damage indirectly to DNA, proteins, and lipids of bacteria cells through these free radicals resulting in the destruction of bacteria cells. Studies have shown that UVA is more effective in generating

ROS compared to UVB and UVC and the oxidative damage caused by UVA exposure is irreparable. For practical applications, a newly-developed hybrid lighting system coupling both visible white light and UVA (405 nm) has been retrofitted in public areas especially in medical facilities and senior care centers where disinfection of air and surfaces can be done over a long period of exposure with or without the presence of humans. This innovation has helped to reduce the rate of healthcare associated infections (HAI) while providing a workable lighting environment simultaneously.

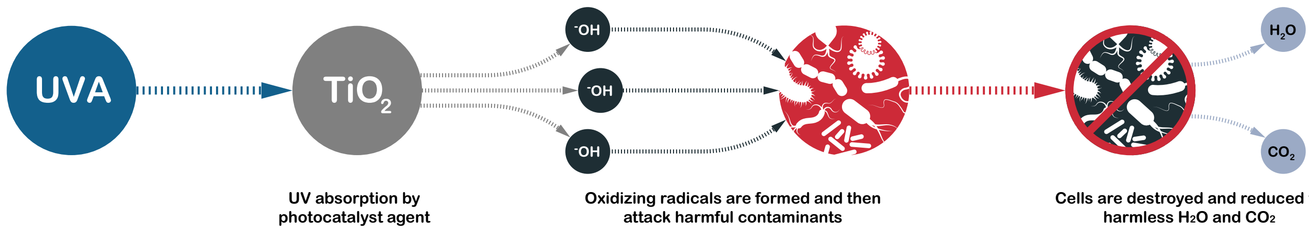
Figure 3: The mechanism of visible light disinfection



Photocatalytic Oxidation

Another effective disinfection method using UVA radiation is photocatalytic oxidation (PCO) which has been widely used in many applications to remove organic contaminants in both water and air. The process involves exposing UVA radiation typically at 385 nm to photocatalyst agents such as TiO2 (Titanium dioxide) and ZnO (Zinc oxide) to produce free radicals (Figure 4). These highly reactive free radicals then attack VOCs (Volatile Organic Compound), bacteria, mold, and fungus—breaking them down into harmless compounds such as carbon dioxide and water. Although both visible light disinfection and photocatalytic oxidation work similarly by utilizing the oxidation properties of UVA wavelength, photocatalytic oxidation is able to accelerate the photoreaction rate of free radicals generation. Some of the many applications that benefit from PCO using UVA include air purification coupled with air filters to eliminate VOCs and mold buildup as well as water treatment systems integrated with a photocatalytic reactor to inactivate bio-pollutants. In food processing and storage applications, PCO can extend the shelf life of food products by effectively reducing ethylene gas concentration and eliminating unwanted odors.

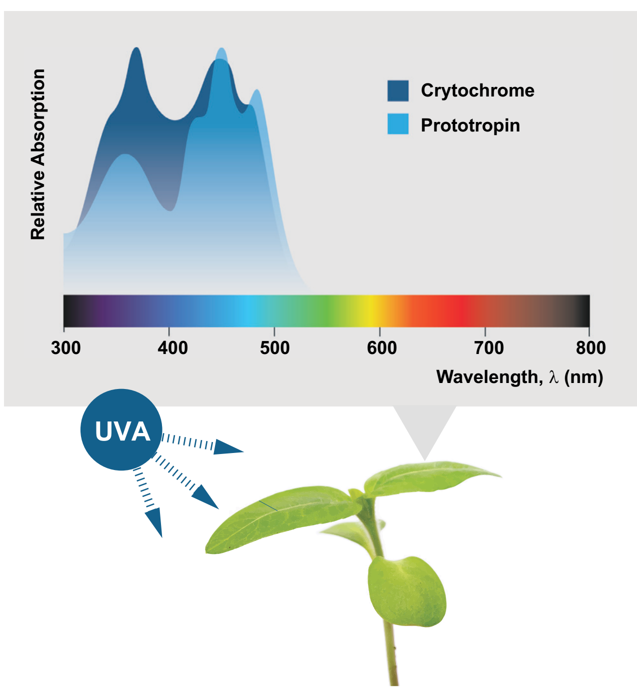
Figure 4: Photocatalytic Oxidation Mechanism



Horticulture

Light is absolutely essential for all plants as it is the key component to their growth and development. The spectral properties of light can influence the response of plants from seed germination to flowering and fruiting. In recent years, the technological advancement of LEDs has contributed remarkably to the explosive growth of indoor and urban farming where space and climate used to be the constraints of traditional farming techniques. Only with LEDs, farmers have the ability to fine-tune the spectral bands including the UV region to optimize growth on the cultivated plants.

Figure 5: Spectral Action of Plants on UVA Radiation



As plants completely rely on solar radiation for energy, they have multiple complex photoreceptors designed to detect light in the environment to optimize photosynthetic potentials. These receptors can detect and absorb specific wavelengths in light to trigger certain biochemical responses in the plant. The photoreceptors that are responsible for blue and UVA radiation are mainly cryptochromes and phototropins where absorption mainly occurs within the 350 to 500 nm range. Blue and UVA radiation regulate a variety of plant morphology responses such as hypocotyl elongation, phototropism, circadian rhythms, flowering time, and so on. They also regulate the production of secondary metabolites which affects the aroma, taste, color, as well as bacteria resistance of the plant. Therefore, most commercially available horticulture LED grow lights utilize a combination of blue and red color LEDs to deliver the desired effect.

Benefits of UVA as Grow Light

In nature, plants grown under sunlight are generally exposed to UVA radiation more than UVB as sunlight is mainly comprised of UVA. Although the negative effects of UV exposure on plants are almost similar to humans, several studies have discovered that with the proper amount of dosage, UVA radiation can further accelerate plant growth and boost the photosynthesis rate. Some of the key benefits of UVAs as grow light include:

- Improves defense mechanisms: Plants exposed to UVA radiation can thicken leaves or epidermis to increase their resistance to bacteria, fungus, and mold infections as well as insects.
- Promotes secondary metabolites productions: Increases flavonoid and phenolic compounds which act as antioxidants to boost the medicinal properties of plants. These compounds also enhance the aroma, taste, and color of certain plants.
- Enhances growing environment: UV exposure makes the reproduction area of plants noticeable to pollinators such as bees. Bees are able to see in the UV spectrum which allows them to navigate and pollinate plants with ease.
- Accelerates germination process: The energy of UVA photons are higher than visible light, hence effectively penetrating through the seed coating allowing sprouts to grow. Also, early exposure to UV shortens the adaption time to a new environment when seedlings are transplanted from a low to high intensity lighting state to increase the production rate.
- Increases plant yields: UVA supplementation in a controlled environment can increase yield by stimulating the photosynthetic rate and biomass production. Several studies have shown that plants exposed to UVA radiation resulted in larger leaf expansion hence higher light interception.
- Boosts medicinal value of cannabis: Having been legalized by over 40 countries mainly for its medical benefits, the rising investment in the world's most lucrative crop is set to further propel the horticulture market growth. UVA can stimulate trichome production to produce higher tetrahydrocannabinol (THC) and cannabidiol (CBD) levels which can be harvested for medicinal purposes.

Phototherapy

UV radiations are often linked to well-known risks such as sunburn and premature aging but they can also be used to treat various medical conditions ranging from skin disorders to psychiatric illnesses. As UVA is able to penetrate deeper into the human skin, one of the best known benefits is the ability to boost the production of Vitamin D in the human body which is crucial for calcium and phosphorus absorption. For such therapy man-made conventional lamps such as xenon, mercury, and fluorescent lamps have been the main source of UV radiation. However, prolonged exposure from infrared radiation emitted by these lamps may potentially cause undesirable side effects and serious health issues on treated patients. By adopting LED technology into phototherapy, such health issues and discomfort can be greatly reduced as LED phototherapy treatment is known to be non-invasive and generates less heat—hence it requires no healing time. In addition, it can deliver the desired spectral bands that are effective for specific treatments. The advancement and versatility of UV LEDs has expanded the applications for both medical and dermatology treatments. The usage of UVA LEDs in phototherapy includes:

- Skin disorders: Numerous studies have shown that light treatment with UVA radiation has successfully treated a number of skin conditions such as psoriasis, atopic dermatitis (eczema), and vitiligo. The most common type of UVA phototherapy is PUVA combining the use of UVA radiation and Psoralen, a photosensitizing agent that makes the skin more sensitive to light. Recently, phototherapy with UVA1 (340 to 400 nm) is increasingly being used due to its non-erythemogenic effect (redness of skin).
- Neonatal jaundice: Reduces the bilirubin level where UV radiation is being absorbed into the skin resulting in the breakdown of bilirubin into compounds that newborns can exert. Newborns are usually treated while covering the eyes or with a BiliBlanket (delivering light through fiber optics) covering the infant.
- Mood and sleep disorders: Sleep-related issues such as seasonal affective disorder (SAD) and circadian rhythm sleep disorder (CRSD) can be treated with light therapy by making up for the loss of sunlight exposure in order to reset the biological clock in the human body. This regulates the sleeping pattern and positively affects the mood and emotional conditions of treated patients. Studies have shown that using full spectrum light with UVA can effectively reduce the depressive behaviors of patients rather than relying on antidepressant medication.

- Wound healing: The combination of UVA radiation and surgery provides a higher success rate to cure keloid and hypertrophic scars. Studies have shown that UVA1 can effectively inhibit scar formation without damaging the cells.
- Pre-cancer: Early-stage cancer such as actinic keratoses can be detected and treated effectively with photodynamic therapy (PDT) which involves UV and photosensitizing agents. This treatment is non-invasive and non-toxic with minimal side effects.
- Acne treatment: Near-UVA radiation ranging from 405 nm to 425 nm can eliminate P.acnes bacteria found in the skin which causes acne. Bacteria are eliminated when free radicals are produced during near-UV light absorption by the bacteria to reduce inflammation.

Product Offering

The 3535 Surface Mount UV LED series offered by Broadcom are packaged in a compact 3.5 mm × 3.5 mm footprint. Available in 1W and 3W, the high-power UV LEDs operate in the UVA spectral range from 365 nm to 425 nm and are suited for applications such as curing, disinfection, horticulture, and phototherapy. The designs feature either silicone or quartz glass optic materials, are highly transparent to UV radiation with excellent light transmission efficiency, and are able to withstand prolonged UV exposure with minimal material degradation overtime. In addition, quartz glass possesses unique properties such as greater resistance to harsh chemicals, deformation, and contaminants enabling its use in harsh environments where rigidness is required. Different beam angles are available as well, as they determine the width and amount of light intensity being distributed onto the targeted area. Selecting the corresponding beam angle can ensure sufficient and uniform light coverage without wastage. Wider beam angles at 130° and 60° are suitable for illuminating large workspace environments or surfaces while a narrower beam angle of 35° is suitable for applications that require a more concentrated beam or higher intensity to eliminate the need for secondary or collimating optics.

For additional information on the Broadcom 3535 Surface Mount UV LED series, visit broadcom.com.

Figure 6: Broadcom 3535 Surface Mount UV LED Series

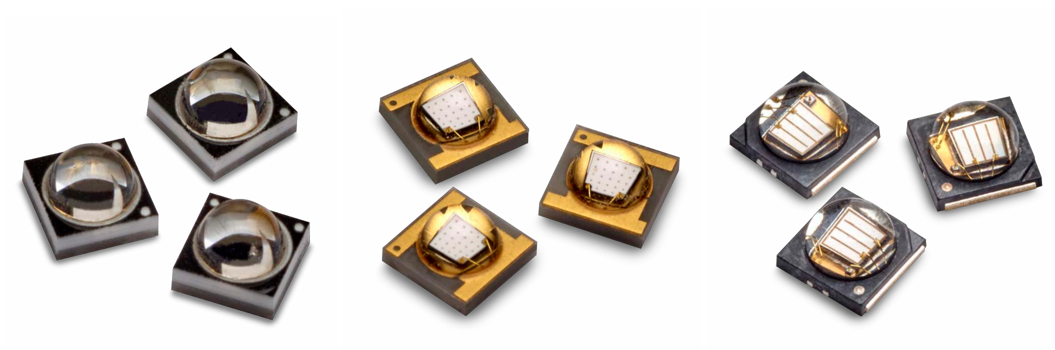


Table 1: UV LED Product Selection Table

Part Number	Wattage	Optic	Viewing Angle, $2\theta_{1/2}$	Peak Wavelength, λ_p	Radiant Flux, Φ_e	Thermal Resistance, $R_{\theta j\text{-}s}$	Test Current
AUV4-PSD0-0MP0H	1W	Silicone	130°	385 nm	455 mW	8 °C/W	350 mA
AUV4-PTD0-0MP0H				395 nm	455 mW	8 °C/W	350 mA
AUV4-PUD0-0MP0H				405 nm	455 mW	8 °C/W	350 mA
AUV4-PVD0-0MP0H				415 nm	455 mW	8 °C/W	350 mA
AUV4-PWD0-0MP0H				425 nm	455 mW	8 °C/W	350 mA
AUV3-SQ62-0RT0K	3W	Quartz	60°	365 nm	1020 mW	6 °C/W	700 mA
AUV3-SS62-0RU0K				385 nm	1020 mW	6 °C/W	700 mA
AUV3-ST62-0RU0K				395 nm	1020 mW	6 °C/W	700 mA
AUV3-SQ32-0RT0K			35°	365 nm	1020 mW	6 °C/W	700 mA
AUV3-SS32-0RU0K				385 nm	1020 mW	6 °C/W	700 mA
AUV3-ST32-0RU0K				395 nm	1020 mW	6 °C/W	700 mA
AUV4-SQ61-0QS0J		Silicone	60°	365 nm	960 mW	4 °C/W	500 mA
AUV4-SS61-0QT0J				385 nm	980 mW	4 °C/W	500 mA
AUV4-ST61-0RT0J				395 nm	1000 mW	4 °C/W	500 mA
AUV4-SQD1-0RT0J			130°	365 nm	1030 mW	4 °C/W	500 mA
AUV4-SSD1-0RU0J				385 nm	1050 mW	4 °C/W	500 mA
AUV4-STD1-0SU0J				395 nm	1080 mW	4 °C/W	500 mA