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Considerations When Transitioning from Lamp-based to LED-based Radiant Flux Sources

Introduction

Lamp-based radiant flux sources have served as a practical solution for irradiance and spectral calibration for decades. Whether utilizing the broadband characteristics as irradiance references or using the well characterized and predictable spectral peaks as wavelength standards, the precise output parameters of lamp-based light sources has proven to be an accurate and reliable tool for diverse applications including camera and image sensor calibration, ambient light sensor calibration, characterizing photodiode responsivity, illuminant stimulation and diagnostic medical imaging to name a few.

Rapid advancements in solid-state lighting technology have led many to consider abandoning their lamp-based standards in favor of LED-based systems. Based on the highly efficient and long-lived performance of LED light sources, their compact footprint and instant-on capabilities, they are the natural choice. However, replicating the precision performance of a lamp-based reference standards in terms of intensity, intensity stability, and spectral performance (often simultaneously) presents a number of design and cost challenges in terms of LED-based systems.

Here we will explore the performance requirements that LED-based sources must achieve to effectively replace lamps in these application areas and how the cost-points of the two solutions compare, both in terms of initial cost and ongoing maintenance costs.

Discussion

Lamp-based Sources

The spectra emitted from lamps is a result of electrons residing in an excited energy level, falling to their stable, ground state. The levels themselves are defined by atomic characteristics of the emission source material. Because this excitation and emission is a well understood and fully characterized process, the emitted wavelengths from lamp filaments are considered to be absolute.

In calibration applications, lamp-based solutions are often bundled together in the interests of achieving the utmost precision. For instance, a broadly emitting calibrated irradiance lamp such as tungsten halogen (Figure 1), incorporating a stabilized radiometric power supply, achieves power level accuracies within a few percent across a broad spectrum. Coupled to this might be a spectral line lamp, such as Mercury (Figure 2), which emits relatively narrow spectral peaks at known wavelengths, enabling spectral calibration. Often times, these systems are used in conjunction with optical filters, gratings or other components for further spectral selection or intensity control.

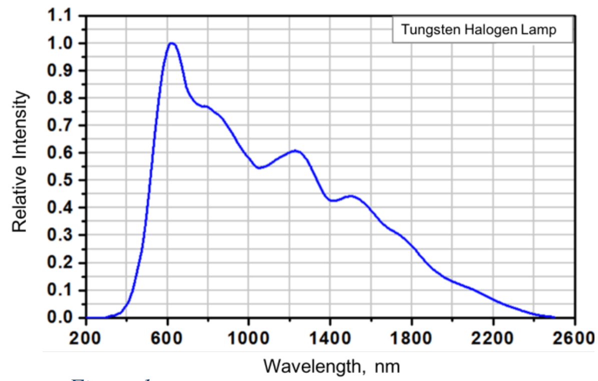

Figure 1

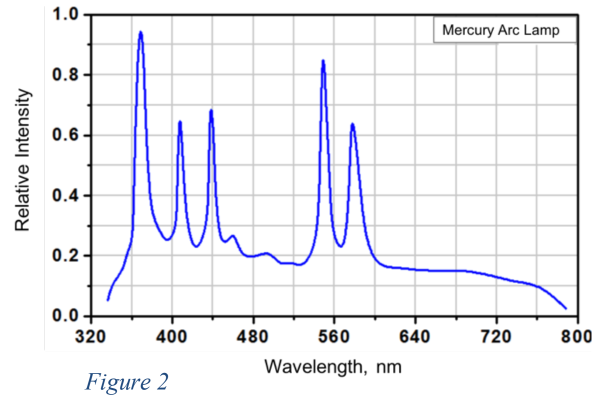

Figure 2

Advantages of Lamps

Lamps have a number of favorable attributes. For example, in applications requiring a broad spectral range, a halogen-based source can deliver light from 350 nm in the ultraviolet, to as high as 2,400 nm in the near infrared. The blackbody spectral error for such sources can be extremely low and combining certain lamps with gratings and/or filters can allow a user to achieve essentially any color temperature.

While the initial cost of a lamp-based system, depending on requirements, can range from a few hundred dollars to as much as $15,000, replacement lamps are relatively inexpensive, with most replacement lamps available for $1,000 or often much less. There is also a certain ubiquity with lamps, resulting in a broad supply base and many installation, calibration and service organizations.

Disadvantages of Lamps

The primary disadvantage of lamp-based solutions is lamp lifetime. Lifetime expressed in hours is calculated at design voltage and under ideal laboratory conditions. Deviation from design voltage will result in decreased values for lamp life. This deviation will also alter values of current consumption, brightness, and color temperature. When known, precise output parameters are key – and they usually are in calibration-related applications – there is only a finite period over which a lamp can predictably perform. In most precision-oriented applications, this is on the order of several hundreds of hours. Beyond which, the spectral performance cannot be guaranteed.

Cold Start-up time can also be a challenge for lamp-based sources. System manufacturers typically recommend a 15-30 minute wait before use. This is largely related to achieve thermal stability, considering that lamp operating temperatures are typically on the order of 150 to 250° C. While temperature of the lamp itself is reached within some minutes, the associated and surrounding components must stabilize at this temperature.

Related to this is switching time. Again, due to the higher operating temperatures, if optical filters, iris diaphragms, etc., are being used in conjunction with the lamp, some minutes are required to re-stabilize when new components are introduced into the optical train.

Narrow band capabilities, as discussed above, can also become an obstacle with lamp-based systems. For example, switching from a broadband illumination source to a narrow-band source requires external components, which add cost and complexity. As moving parts, extra elements such as filters or attenuators introduce potential points of failure into the solution. That is, if the narrow-band requirements can be achieved. Often times, a multiple lamp-based systems are employed in applications requiring both broadband and narrow-band light sources, increasing acquisition and maintenance costs – and consuming space in the laboratory or on the production floor.

The tolerance for mechanical shock is obviously quite low for lamp-based systems, particularly while in operation. Special handling requirements must be observed, both in terms of breakage and in some cases for disposal (for instance, Mercury-based sources).

We also must consider that very little investment is occurring in further development of lamp-based technology. Obsolescence is a very real threat, particularly considering the materials used in certain of these lamps, and the ever-decreasing demand for the devices in general. This will ultimately impact both cost and availability.

Finally, power consumption can be quite high for lamp-based systems, at least in comparison to their LED counterparts. We will discuss this further in the following paragraphs.

LED-based Sources

Light-emitting diodes, or LED's consist of a p-n junction diode that emits light as current passes through it. Electrons recombine with electron holes within the semiconductor junction, releasing energy in the form of photons. The emitted wavelength is determined by the bandgap of the semiconductor materials and/or their dopant levels.

Disadvantages of LED Based Sources

Since the emission wavelength of an LED is fundamentally determined by the bandgap of the semiconductor, a particular LED emits only a fairly narrow wavelength spectrum. While this is useful in applications requiring a wavelength reference standard, applications requiring broadband output must incorporate multiple LED's of different wavelengths. In addition, semiconductor materials and their resulting bandgap is not unlimited. In other words, certain wavelengths of light are simply not possible with direct-emitting LED's. We will discuss this further in the next section.

LED wavelength also shifts with changes in operating current, and to a lesser, but measureable extent, with changes in junction temperature. As a result, unless steps are taken to control junction temperature and account for current-related wavelength shift, use as calibration standards can be tricky.

Due to their highly directional nature, multiple LED devices are normally required to deliver uniform intensity over the required area. These multiple devices can add to system cost and size, and steps must also be taken to integrate the light from multiple emitters in the interests of achieving good uniformity over the desired field of view.

Advantages of LED Based Sources

Rapid technological advancement is a key advantage of LED technology. The light output of LEDs has essentially doubled every 36 months since the 1960's (for more information, see Haitz's Law). We can expect continued rapid advances in terms of spectral intensity, wall-plug efficiency, longevity and cost for many years to come.

One particular shortcoming of LED devices also turns out to be a key advantage – and that is their relatively narrow wavelength emission. Blue-emitting LED's, when launched into phosphor-coated optics, result in broadened spectral emission. In these devices a $Y_3Al_5O_{12}$:Ce ("YAG") phosphor coating absorbs some of the blue emission and, depending on the specific formulation, produces yellow, green or red light. The resulting mixture, including the fundamental blue wavelength, is excellent for illumination in terms of color rendering.

Through a software interface, individual LED devices can be addressed and adjusted to produce broadband output, specific reference wavelengths, emulate any number of lamp-based sources, simulate optically filtered light sources, or even allow the user to design their own spectral output. This occurs without the use of optical filters or opto-mechanical components – thus eliminating moving parts, their associated size and cost, and reducing potential points of failure. Figures 3 and 4, below, show the Gamma Scientific SpectralLED® Tunable Light Source operating in broadband or custom spectra modes.

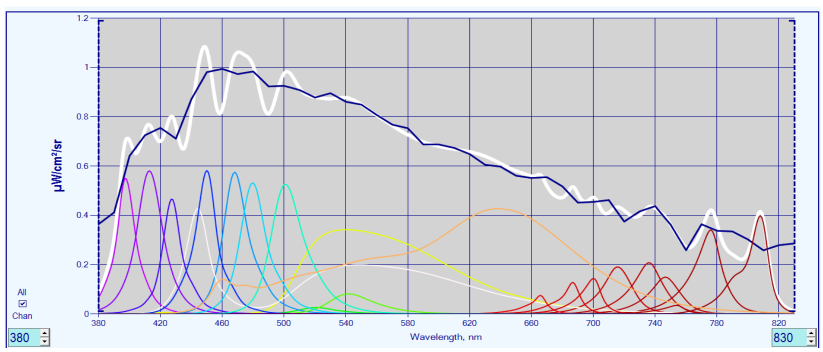

Figure 3 SpectralLED® emulation of D65 source. Blue line represents target spectra, white line represents actual output.

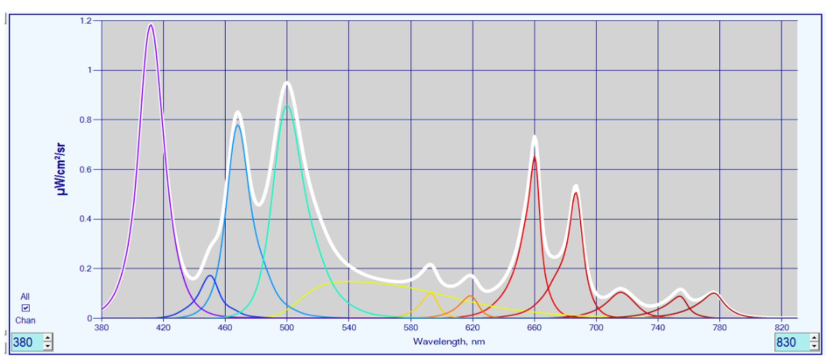

Figure 4 User selected spectra from SpectralLED® light source.

Another significant advantage is that the operating lifetime significantly favors LED technology versus lamps. While a discussion of reliability parameters is beyond our scope here, L70/B50 lifetime performance for LED's is in the range of 10,000 to 40,000 hours or often much more. [For reference, L70/B50 is the point where half the devices have declined to 70% of their original intensity.] This lifetime factor has an enormous impact on cost of ownership – particularly where system down-time associated with install and recalibration are significant cost factors.

Due to the use of multiple light emitters, with an appropriate control and monitoring system – an LED-based solution has the inherent ability to quickly adjust and precisely maintain a desired output intensity and spectral profile. Along these same lines, one can maintain a desired spectral profile over a broad range of intensities or maintain consistent intensity over a broad range of spectral profiles. This switching time is typically tens of msec with a proper control interface such as the SpectralLED® system.

Because LED's stabilize at operating temperatures that are approximately an order of magnitude lower than lamps, cold start-up time is typically on the order of 1-2 seconds. Their high wall-plug efficiency also results in less waste heat, which can be a significant benefit in precision test environments. This rapid start-up time of LED systems can also be used to dramatically increase their operating lifetime, in that the devices can simply be powered down when light output is not needed, and quickly re-started when required for use. This is simply not possible with a lamp-based solution.

It almost goes without saying, but the tolerance to mechanical shock of LED devices is far superior to lamps. For specifics, please see Table 1. Instead of the light source being the component most susceptible to breakage in the system, LED-based light sources are often the component *least susceptible* to breakage.

Comparison Factor Summary

As there are numerous lamp-based sources, and a multitude of LED-based sources on the market, a side by side comparison can be difficult. However, Table 1 selects a specific application area (image sensor calibration) and compares the Gamma Scientific SpectralLED® Tunable Light Source with the Halogen lamp-based system historically used in this application.

Table 1

	SpectralLED® Tunable Light Source	Halogen Lamp-based Light Source
Operating Lifetime Hours (L70 / B50 or based on Calibration Guarantee)	25,000	300
Cold Start-up Time	< 2 seconds	15-30 minutes
Ability to Power Down Between Test Events (increased lifetime)	Yes	Unlikely due to long start-up time
Intensity Stability	Better than 0.01%	2.5%
CCT Accuracy	Within 10k	20 to 50k
Self-Calibration	Automatic, up to 2 years(1)	None
Calibration Failure Alerts	Yes	Very Limited
Spectral Range	380 nm to 1000 nm or 900 nm to 1700 nm	350 nm to 2400 nm
Service Downtime	~ 4 hrs / 10,000 operating hrs	~ 6 hrs / 300 operating hrs
Switching Time	< 50 msec	5 minutes
Narrow-band Capabilities	Pseudo Monocrometer	Requires additional components
Tolerance for Mechanical Shock	1500 G for 0.5 msec	10 G for 15 msec
Social Responsibility	66% Lower Power Consumption	
Required Opto-Mechanical Accessories	None	Filters, Iris, Shutter
Required Electrical Accessories	None – self contained	Precision power supply
Emitter Temperature	Typically 25 to 40°C	Typically 150 to 250°C
Product Lifecycle of Light Source Technology	Emerging to Growth Phase	Mature to Obsolescence Phase

(1) Regulatory compliance in some applications may require annual calibration certification.

The Comparison That Often Matters Most – Cost

Cost comparison of lamp versus LED-based sources is not simply a matter of examining the 'sticker price' for a new, out of the box solution. Usage profile is a very important variable, as are a number of other important factors.

Down-time cost is often the most significant contributor to cost of ownership. For example, in an image sensor foundry, test equipment down-time can be tens of thousands of dollars per hour. If your calibration light source requires a lamp replacement and subsequent recalibration every few hundred hours, the costs add up very quickly.

Repair labor cost per hour is also a consideration. That is to say, the cost of the Service Technician's labor. If using internal resources, one must consider the added costs of fringe benefits for the individual, along with opportunity cost in terms of other things the same personnel could be doing (for instance, yield or productivity improvements).

Equipment usage profiles are the multiplicative factor to be considered. For instance, if your light source is operated 8 hours per day, 5 days per week – lamp replacement must occur approximately every 6 weeks.

Capital equipment depreciation rates should also be considered. Although the LED-based solution is initially higher in cost, these costs can be amortized over several years. The lower initial cost of the lamp-based system would also be amortized, but costs associated with down-time and repair labor hit your bottom line immediately and repeatedly throughout the entire usable lifetime of the device.

Figure 4, below considers the above factors over a 24-month period. It is assumed that the both solutions require an annual calibration check, which, aside from the amortized original purchase price, is the only ongoing cost of the SpectralLED® system. Note that although the wall-plug efficiency of the LED-based system is far greater than that of a lamp, energy consumption is not a significant operating cost factor in either case, and we therefore ignore those costs for the purposes of our analysis here.

User Inputs		
Down-time Cost	$ 1,000	per hour
Repair Labor Cost per Hour	$ 45	per hour
Tool Usage per Day	8	hours
Tool Usage Days per Week	5	days
Capital Equip Depreciation	24	months

Assumptions		
Lamp Lifetime	300	hours
Replacement Service Time	4	hours
Lamp Cost	$ 150	
SpectralLED Cost	$ 22,500	
Lamp-based System Initial Cost	$ 10,000	
SpectralLED Annual Calibration	$ 1,000	

Lamp Usage per Month	173	hours
Lamp Changes per Month	0.58	

Cost per Lamp Change	$ 4,420
Lamp Usage Cost per Month	$ 2,552

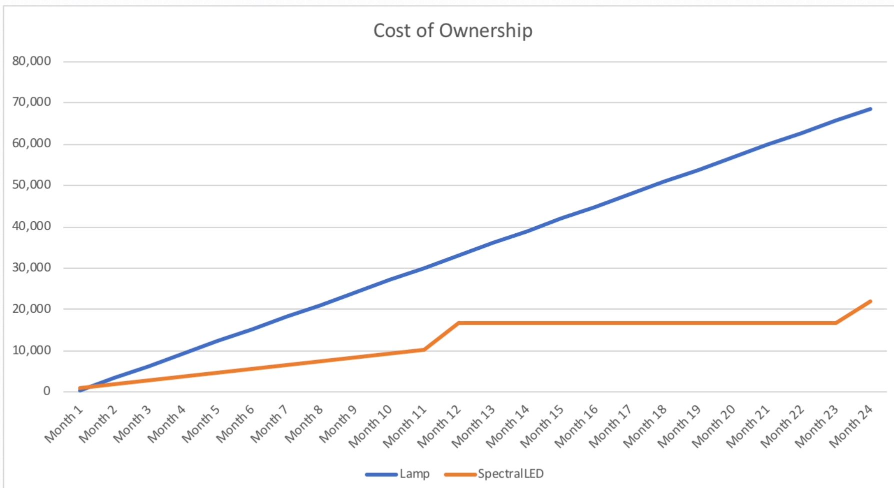

Figure 5

As you can see, based on the assumptions shown, although a SpectralLED® device has an initial cost that is more than twice that of and equivalent lamp-based system, the lamp system's cost quickly and permanently surpasses it -- by more than a factor of 3 after just 2 years of use.

When is a lamp-based system still the best choice? The answer depends on the factors that are most important to your specific application. For example, if a lamp-based light source is only used a handful of hours per month, it could take multiple years to recoup the higher cost of an equivalent LED-based solution. On the other hand, if flexibility is important, the LED-based solution provides nearly infinite possibilities in terms of lighting simulation from a single SpectralLED® unit, which is simply not possible with a lamp-based source. In addition, in low duty cycle usage profiles, it's difficult to know if your lamp is fully calibrated after sitting idle for some months. A SpectralLED® system on the other hand, self-calibrates at each start-up to within a fraction of a nanometer, depending on the monitoring options installed in the unit.

Summary

Lamp based light sources have served as a calibration standard workhorse for several decades, and under certain usage profiles, continue to be a cost-effective and viable solution. The output spectra is known and well characterized, and replacement lamps are relatively inexpensive. There can be however, significant hidden costs involved in the operation of lamp-based systems, including installation labor, and more significantly, down-time costs during lamp replacement and calibration. The flexibility in both intensity and spectral output is limited and/or requires additional components, and looming obsolescence introduces longer-term availability risk.

LED technology is evolving rapidly. While multiple LED emitters are required to emulate a lamp's output, an integrated solution can provide highly valuable flexibility in terms of intensity and spectral control. Steps must be taken to ensure long-lived and stable performance from LED's, but expertise in control electronics is well established. Initial deployment costs for LED-based solutions such as the SpectralLED® from Gamma Scientific are higher than for lamp-based systems, but particularly in production environments, their long operating lifetime and minimal service costs very quickly make them the most cost-effective solution. Even in the laboratory environment with lower usage profiles, a single SpectralLED® can emulate a multitude of lamp outputs, allowing for a single unit to replace multiple lamp-based units. In the increasingly rare case where lamps continue to be the best solution, Gamma Scientific continues to sell and support a variety of high precision lamp-based solutions.

About

For over 50 years, Gamma Scientific has delivered highly unique, state-of-the-art measurement solutions for manufacturers and users of light sources, sensors and displays. Products include high precision spectroradiometers, calibration light sources, goniophotometers, integrating spheres, thin film measurement systems, and LED testers and sorters. The company also operates an ISO/IEC 17025, NVLAP accredited laboratory (NVLAP Laboratory code 200823-0) for calibration and testing.