The Radiometry & Photometry of Divergent and Other ‘Difficult to Measure’ Light Sources

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Sources of optical radiation that exhibit high powers, large beams, extended source sizes, high divergence or dynamic beam displacement present a significant challenge to those wishing to determine their power in an accurate, repeatable fashion. The integrating sphere provides an elegant solution and offers an increased accuracy alternative to regular optical power meters used with ‘difficult to measure’ sources, such as LEDs, lamps, projectorised sources, optical fibres, laser diodes, VCSELs and laser diode stacks or bars. Compared with a bare photodiode detector, the integrating sphere captures the full beam from such sources and reduces the effect of the non-uniform spatial response that many detectors exhibit. Sphere response is polarization insensitive and serves to attenuate the optical beam onto a photodetector, allowing much higher power sources to be measured with sensitive, fast response silicon, germanium or InGaAs photodiodes. An enhanced design of integrating sphere that has been optimised for divergent, semi-collimated sources (for example, LEDs and laser diodes) is considered and the improvement in spatial integration that this design provides is compared with the performance of a simple, general purpose integrating sphere. Three case studies are presented to illustrate the real-world solution that integrating spheres provide in quantifying challenging light sources.

The Limitations of Photodiode & Thermal Detectors

In optical radiation measurements, the optical power (luminous flux in lumens or radiant flux in watts) of a light source is most often determined using a photodetector with a calibrated responsivity (in amps per watt, or amps per lumen if the detector is filtered to give a photopic response). For practical purposes, a photodiode (silicon, germanium or indium gallium arsenide) is used for most applications in the wavelength range from the UV to near IR (200-1800nm), although thermal (calorimeter, thermopile) detectors can be used with the high power beams from collimated laser sources.

Photodiodes have several significant drawbacks that limit their utility when trying to measure divergent, diffuse, extended area, high power or any other non-collimated source, such as lamps, projectorised sources, optical fibres, laser diodes, LEDs, VCSELs and laser diode stacks or bars. Firstly, photodiodes are generally only available with sensitive areas of up to about $1cm^2$. Secondly, the saturation flux of most photodiodes is of the order of $1mW/cm^2$. This imposes practical restrictions on the type of light source that a bare photodiode can measure. The source must be of a low enough power not to saturate the diode in order to avoid an inaccurate, non-linear response. Further, any divergent source must be positioned very close to the detector to avoid overfilling its active area which would lead to a consequent under-recording of the beam flux. Some sources (for example a light bulb or diode array bar) have an extended emitter area and simply cannot be measured using a bare photodiode alone. Beams with areas larger than the photodiode active area, or with significant dynamic displacement, simply cannot be measured directly using a bare photodiode.

Calorimeter detectors are an obvious choice to measure the output of collimated, high powered lasers. Thermal detectors are available with input apertures of up to 50mm or more, so broad-area beams can also be tested. Apart from the same geometric limitation described above for extended and diffuse emitters, the main factor limiting the utility of thermal sensors with low power lasers and non-laser sources is their relative lack of sensitivity. Whereas most photodiodes have a sensitivity of a few picowatts, a typical 10-20mm aperture calorimeter will exhibit noise levels that limit their use below a few milliwatts, while a typical 50mm aperture thermal detector can only be used above about 200mW. Thermal sensors do, of course, exhibit a broad spectral range and can directly handle very intense beams but their utility with low to moderate power or divergent, extended and large area sources is very limited.

It is for these reasons that we turn to the integrating sphere as a simple solution to often challenging problems in optical radiation measurement.

The Integrating Sphere

Since its invention in 1892 (by British scientist W.E. Sumpner), the integrating sphere has provided a unique solution in optical radiation measurement, albeit one that is even today, not widely understood. An integrating sphere is a hollow, spherical chamber coated internally with a high reflectance coating that exhibits lambertian (i.e. diffuse) reflectance. Spheres are used either as directionally-insensitive collectors of light (combined with photodetectors) or as sources of uniform light (when internally illuminated). A collage of typical integrating spheres (150-300mm diameters) is shown in Figure 1.

Figure 1: Collage of Typical Integrating Spheres (courtesy of Labsphere)

Integrating spheres are used to record the total radiant flux (in watts) or luminous flux (in lumens) of sources of optical radiation operating with wavelengths in the spectral range from 200nm to greater than 20μm. The diffuse, high reflectance interior coating of an integrating sphere serves to spatially integrate all of the radiation entering the sphere, such that the light intensity produced at almost any point on the sphere surface is directly proportional to the total flux from the light source. It follows that a photodetector mounted on the wall of the sphere receives the same amount of radiation as nearly every other part of the sphere wall. Because the photodiode is uniformly illuminated by the sphere, the effect of any spatial non-uniformity in the detector's response is greatly reduced. The uniform but random distribution of optical radiation within a sphere also serves to eliminate the effect of any beam polarization on the detector reading.

A simple integrating sphere for beam power measurements (see Figure 2) would be designed with an input port through which the beam from the light source enters, and a second port on which the photodiode is mounted. It is common for the input and detector ports to be located with a 90 degree separation and for an internal baffle (or screen) to be fitted to the sphere to prevent direct illumination of the detector by the source, which would be the case if the emitter were diffuse or highly divergent. Without the baffle, the detector would see a disproportionately large signal and this would lead to a significant over-recording of the beam power. The baffle is coated with the same, diffusely reflecting material as the integrating sphere wall.

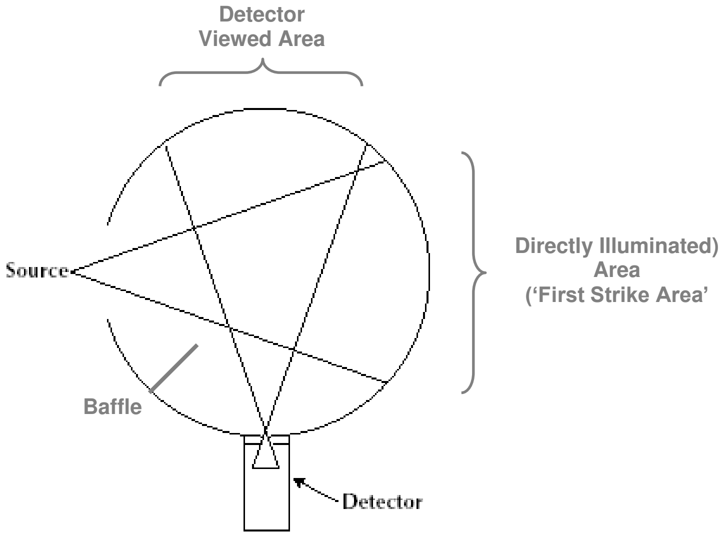

Figure 2: Simple Integrating Sphere Design

An integrating sphere for total flux measurements operates as a geometrically insensitive collector of light. A photodetector mounted at the wall of the sphere will see a radiance that is linearly proportional to the amount of light that enters the sphere, provided that there is no direct line of sight between the source and the detector. It follows that if more than one detector is mounted at the sphere wall, each will see the same light level. This principle is used to make dual-band sphere radiometers that use a silicon detector for making power measurements from 200 to 1100nm and either a germanium or InGaAs detector for wavelengths between 800-1800nm. Furthermore, a connector for an optical fibre can be mounted on the sphere wall which serves to couple a small amount of light to an optical spectrum analyser for source spectral analysis.

The ideal sphere has a coating with a very high level of reflectance. Most commercially available coatings for integrating spheres have nominal reflectance levels between 94 and 99%. The higher the reflectance, the greater the sphere throughput onto the photodetector, to the benefit of detector sensitivity and reduced detector noise offset levels. Conversely, the lower the throughput of a sphere the greater the attenuation the input beam experiences and this property is used to good effect when using an integrating sphere to measure the flux of high power sources. It is however important that the "loss" of optical power that a sphere introduces is allowed for in the calibration of the photodetector mounted on it; erroneous readings will be obtained if the detector's own responsivity is relied upon.

Calibrations of the spectral responsivity of a detector/sphere combination are usually performed using a substitution process. This requires that a stable source is first measured using a reference detector that has been calibrated at a national standardizing laboratory, or has itself been calibrated using traceable transfer standards. This measurement records the reference flux. The detector/sphere combination is then substituted for the reference detector and the new detector signal recorded. Provided that the illuminating source remains constant between these measurements, the ratio of detector signals equals the ratio of source fluxes, and the responsivity of the detector/sphere combination can be calculated.

The size of an integrating sphere is primarily chosen according to the power of the source and the size of the beam. For example, if a 25mm diameter input port is required the sphere diameter would typically be 100mm or more so as to maintain the open port fraction below 5% of the entire sphere wall area for the geometrically uniform collection of light. Furthermore, the larger the sphere the greater the attenuation of the input beam, so a larger sphere can be used for higher power beams. Clearly, the larger the sphere, the more expensive and bulky it becomes, but the attenuation that a sphere introduces has the effect of shifting the useful range of a photodetector to higher powers. If we consider the case of a bare silicon photodiode that would have a dynamic range from about 1pW to 1mW, a sphere with a 1000:1 attenuation factor would allow the same photodiode to be able to record beam powers from 1nW to 1W. The exact level of sphere attenuation is a function of coating reflectivity, sphere diameter and open port fraction, while the signal received by a photodiode will also be governed by the detector's active area and solid angle field of view into the sphere. These parameters can all be selected to arrive at a sphere/detector combination with the desired level of attenuation for the type of sources it is required to measure.

Integrating sphere coatings are chosen to provide the highest diffuse reflectance in the spectral region of interest. Ideally, coatings should also be spectrally non-selective (that is, they exhibit a wavelength-independent reflectance). For most applications in the 250-2500nm range, coatings based on barium sulphate are commonly used. For superior reflectance, improved measurement sensitivity and enhanced environmental stability in this waveband, thermoplastic coatings based on Teflon™ are available from a number manufacturers. For measurements with sources in the region from 1-20μm, electroplated gold coatings are applied to a roughened metallic substrate (usually brass). Polished aluminium and silvered coatings are not commonly used in integrating spheres due to their relatively low, spectrally-selective reflectance levels. A glossy surface cannot be used as an integrating sphere coating as the sphere would retain a high degree of directional sensitivity.

An Enhanced Sphere Design for Divergent Sources

The demands of measurement accuracy and repeatability dictate that there is no such thing as a "one-size-fits-all" integrating sphere. To function correctly, a sphere for total flux measurements must be designed to take account of the size, position, divergence, any displacement and the power levels of the particular source under test.

The simple sphere model described earlier serves to address the basic problems associated with using bare photodiode detectors with high power, divergent or extended area light sources. However, the signal from a photodiode mounted on a simple sphere can still exhibit a strong dependence on the position, direction and divergence of a light source. It has been stated that the radiance observed by a detector mounted on the wall of a sphere is directly proportional to the flux entering the sphere, provided that the detector cannot directly view the incident beam. In reality, this is too simplistic a model. For example, the area of sphere wall opposite the input that the incident beam illuminates (known as the 'first strike' area) acts as a virtual source and ideally this area should also be screened from the area that the detector views – see Figure 2. A second baffle can be used for this purpose.

However, baffles should be used with caution. Whilst they serve to block the line-of-sight from a source to a detector, they introduce in themselves spatial non-uniformities into the sphere response. Research conducted at Labsphere (www.labsphere.com) has shown that a sphere can be designed for performing more accurate and repeatable measurements on divergent and other sources without the need for baffles. Their Laser Power Measurement Sphere (LPM-040-SF, see Figure 3) features an innovative design which positions the photodiode detector in a non-radial position just below the input port of the sphere. The photodiode is recessed and constrained to view a small area of sphere wall just above the entrance port (Figure 4). As a consequence, a photodiode detector can see neither direct nor indirect radiation from the first strike area for any beam that enters the sphere within a 40 degree cone angle originating from the centre of the plane of the sphere input. The restricted view from the photodiode into this sphere also serves to extend the maximum power level that this sphere can measure, with attenuation of the order of 10,000:1.

Figure 3: Integrating Sphere for Divergent Source Flux Measurements (courtesy of Labsphere)

The reduction in spatial sensitivity that the new sphere design provides was compared with the performance of a typical, general purpose sphere. The spatial response of a simple integrating sphere (100mm diameter, 5% port fraction, 98% reflectance barium sulphate coating) was studied by illuminating the sphere with a collimated laser beam (Helium Neon laser, 633nm, 5mW). A silicon detector was fitted at the sphere wall at 90 degrees separation from the sphere input and with a baffle providing line-of-sight screening between the two. The change in detector signal was recorded as a function of angular rotation of the laser beam in both vertical and horizontal planes. The results are shown in Figure 5 (data set: GP-IS, general purpose integrating sphere). For elevations of up to ± 20 degrees in both X & Y directions, the general purpose sphere was seen to be relatively insensitive to the direction of the source. At >20 degrees however, the area of sphere wall first illuminated by the beam begins to be “seen” by the photodiode, and thereafter, causes large deviations in the measurement data. The baffle also contributed to the non-linear response of the sphere. This particular sphere should therefore not be used with sources that exhibit a divergence of greater than ± 20 degrees to ensure acceptable measurement accuracy and repeatability.

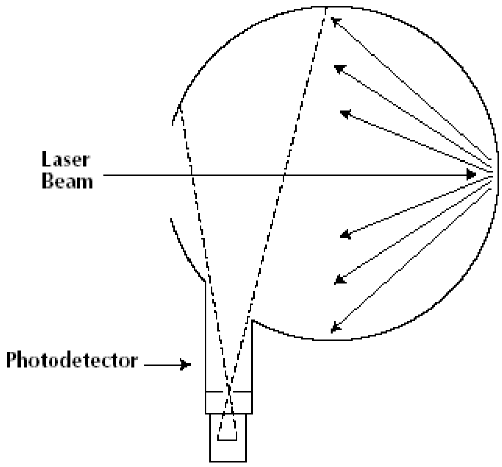

Figure 4: A Baffle-Free Sphere Design for Divergent Source Measurements

The enhanced sphere was subject to the same tests described above and the results are plotted on the same chart, Figure 5 (data set: LPM-040-SF). The LPM sphere was shown to be much less sensitive to input beam variations over a wider range of input angle (± 40 degrees). This improvement results directly from the use of a narrow detector field of view which avoids both line of sight to the source and prevents the detector viewing the extended area that the displaced beam illuminates directly (the first strike area). Clearly, for sources with high or variable angle beam divergence, a sphere with a deliberately restricted detector field of view and no baffles will provide higher accuracy results than would be obtained from a typical general purpose integrating sphere.

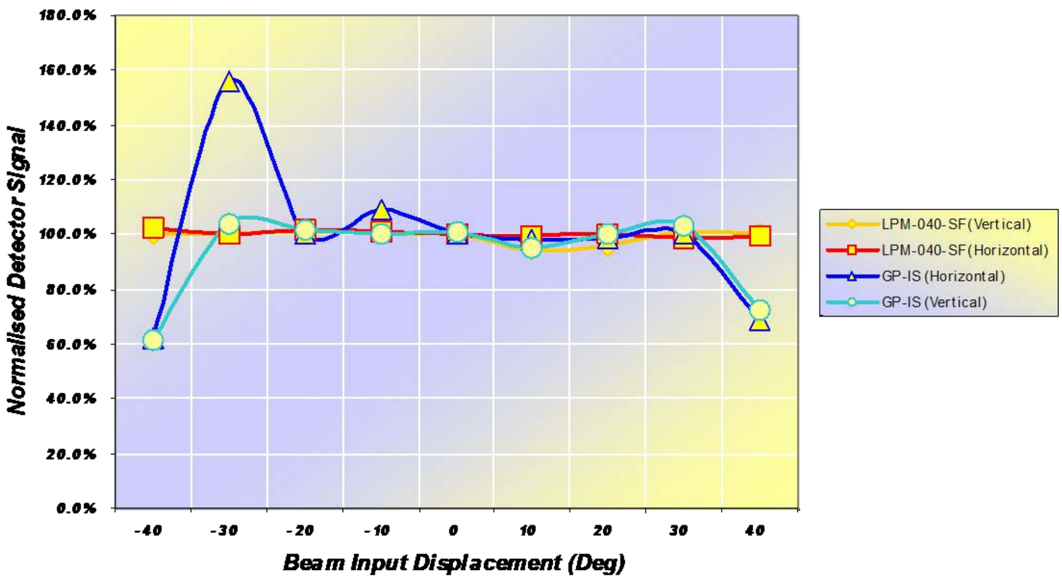

Figure 5: Integrating Sphere Spatial Response

Sphere Design for Extended, Point Source or Diffuse Emitters

The discussion given in the previous section applies in the case of collimated or semi-collimated light sources. For measuring the power from extended, point source or diffuse emitters, an interior-access sphere such as that shown in Figure 6 can be used. A sphere used with internally mounted sources would normally feature hinged hemispheres that allow for ease of interior access. This sphere is equipped with a detector, baffle, auxiliary lamp, lamp mounting hardware, and a lampholder with electrical wiring. Ideally, the sphere diameter should be larger than ten times the diameter of small lamps and devices and twice the length of linear lamps. Baffles are used to shield the auxiliary lamp and detector from direct illumination by the lamp. The auxiliary lamp should be used to allow the measurement of self-absorption by internally placed sources and associated hardware. The detector is corrected for the photopic observer. Spectroradiometers (including diode-array and CCD-detector type) are also used in place of a photodiode detector where readings of the source spectral flux (in watts per nm) are required. The angular responsivity of the detector should be cosine-corrected and this is best achieved using a small satellite sphere in front of the detector. Care should be taken in the design to ensure that the detector does not view only the back side of the baffle – to do so would cause a large spatial nonuniformity in the sphere responsivity and would lead to substantial errors in substitution measurements.

The approach taken to measure the output of a filament lamp using a sphere is instructional. A test source is typically mounted at the geometric centre of a sphere and the detector signal measured and compared to that from a calibrated lamp that is measured separately within the same sphere. Provided test and reference lamps are identical, the ratio of detector signals equals the ratio of lamp fluxes. If the lamps are not physically identical (as is usually the case), a correction can be applied using measurements performed using the auxiliary lamp. The difference in self-absorption between the test and reference sources is recorded as the difference in detector signals when the two lamps are mounted separately within the sphere and illuminated by the auxiliary lamp. These auxiliary measurements produce a correction factor that is then applied to subsequent measurements of that particular type of test source. It follows that an auxiliary correction measurement must be performed for each distinct type of test source.

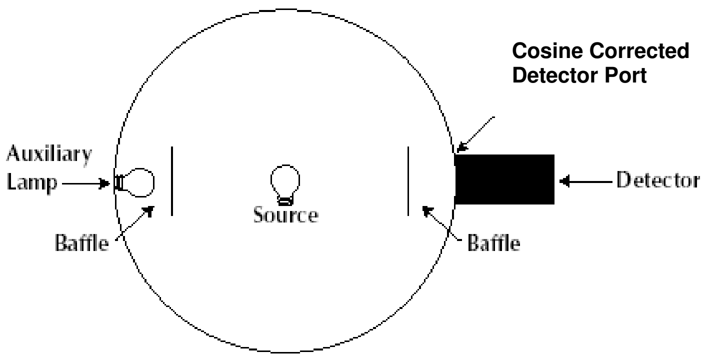

Figure 6: Integrating Sphere for Lamp Flux Measurements

The sphere configuration shown above provides for measurements on a wide variety of sources. Sources that emit highly diffuse beams or sources with extended areas are generally measured when positioned at the geometric centre of the sphere. Such sources could include traditional filament lamps, compact and linear fluorescent lamps as well as discharge or arc sources. LED lamps, LED clusters or array sources can also be measured most accurately when positioned within a sphere. Conversely, semi-directional sources such as projectorised lamps, LED projectors and laser diode arrays are best measured with the source mounted outside and at the wall of the sphere. The "beam" from such sources is generally directed into the sphere in a direction that avoids both direct illumination of the detector and also of the area of sphere wall viewed by the detector.

Applications of Integrating Sphere Radiometry & Photometry

Three interesting, commercial examples of integrating sphere solutions to otherwise challenging optical radiation measurement problems are presented here from the fields of medicine, forensics and consumer optics.

Diomed Ltd (www.diomedinc.com) is a Cambridge, UK-based manufacturer of lasers used in medicine. Diomed's PDT 630 is a diode laser system used in photodynamic therapy (PDT), a treatment for oesophageal and endobroncial cancers. In PDT, a cytotoxic chemical is selectively retained within cancerous tissue and 'activated' by the application of light of a particular wavelength. The output from the Diomed laser (up to 2W at 630nm) is coupled into an optical fibre, the distal end of which is fitted with a cylindrical, diffusing tip which serves to deliver the laser energy uniformly at the treatment site (Figure 7). For accurate treatment dosimetry, the output from the fibre must be measured. Clearly, this is impossible to do using a bare photodiode detector. Instead, Diomed provides each laser with an internal calibration sphere on which is mounted a photodiode. To measure the laser output, the fibre is simply inserted into the centre of the sphere.

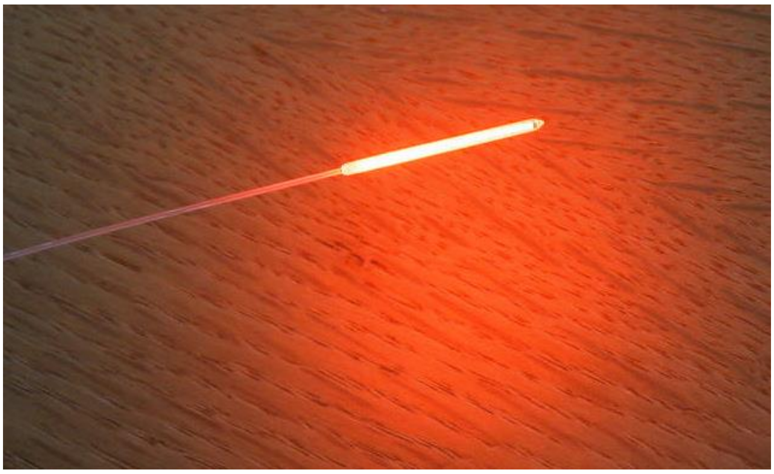

Figure 7: Fibre with Diffusing Tip used in PDT (courtesy of Diomed)

Mason Vactron Ltd of Evesham, UK (www.masonvactron.com) manufactures a range of products for the development, examination and recording of latent fingerprints which are used by police and forensic scientists either in the laboratory or at the scene of a crime. Traditionally, bulky arc lamp sources have been used for scene of crime illumination but Mason Vactron is pioneering the use of LED-based sources as more compact, higher-productivity alternatives. Using advanced LED technology, Mason Vactron have created a range of compact, battery powered, high-intensity forensic light sources for locating evidence at the scene of a crime. The Mason Vactron Crime-lite (Figure 8) provides narrow waveband light for fluorescent excitation at wavelengths in the violet, blue, blue-green and green bands for detecting blood stains, gunshot residues, body fluids, and superglue-treated fingerprints.

Figure 8: LED-based Torch for Forensic Analysis (courtesy of Mason Vactron)

In the Crime-lite, LEDs are clustered to provide high illumination levels, resulting in an output of up to 500 mW, in a low divergence beam. The radiant flux of this semi-collimated, high power, large-area beam is difficult to measure using a photodiode detector, while large area calorimeter detectors do not possess sufficient sensitivity for this type of source. By using a 200mm diameter integrating sphere with a 50mm input port, the power from the Crime-lite is measured conveniently, accurately and repeatably.

Carclo Technical Plastics (www.carclo-optics.com), based in Slough, UK are leaders in the field of LED optics. They have recently developed a range of high efficiency optics for use with the Luxeon range of high power LEDs from Lumileds. Carclo Technical Plastics needed a means of accurately measuring the throughput efficiency of the optics in production. This measurement was made difficult by the fact that the LED optics are available with half angle divergences between 1.5 and 45 degrees and diameters from 20 to 60mm. Consequently the measurements were too difficult to make using standard silicon detectors. The solution was a 250mm-diameter sphere with photometrically filtered (CIE V_λ) response photodetector.

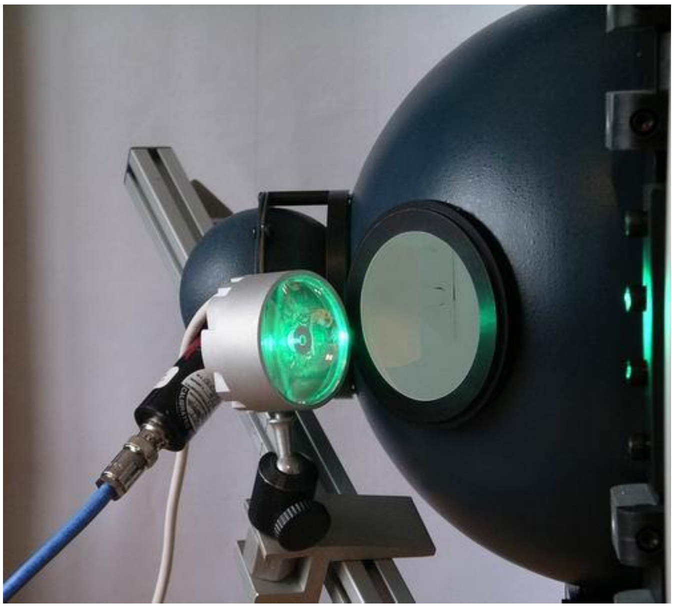

Figure 9: LED Optic (courtesy of Carclo Technical Plastics)

The test measurement requires the comparison of the output of mounted versus unmounted LEDs. Ordinarily, the approach would have been to simply shine the different sources into the sphere and compare the detector signals. The complication here was that the mounted LED was held in a large-area, reflective housing (see Figure 9). The presence of the LED housings could introduce a significant substitution error into the measurement process by reflecting back into the sphere a proportion of the light from the sphere that would normally exit the open port when the bare LED was positioned at the sphere input. To compensate for this error, the simple expedient of an auxiliary correction lamp was employed which served to measure the difference in sphere throughput between the mounted and unmounted LEDs.

Summary

The integrating sphere provides optical engineers with the means of measuring the power from otherwise difficult to measure sources such as lamps, LEDs, laser diodes and optical fibres. When specifying an integrating sphere, consideration should be given to the power and size of the source and also the geometric beam conditions (divergence and displacement) to ensure high levels of measurement accuracy and repeatability. The use of general purpose integrating spheres is to be approached with caution due to the possibility of erroneously high readings caused by the overlap of detector field of view and the area of sphere wall first illuminated by the optical source. With a sphere chosen specifically for the type of source under investigation, measurements of divergent source power are made much more simply, accurately and repeatably.

Further Reading

Readers interested in learning more about the science and application of integrating spheres in optical radiation measurements can download the Labsphere guides to ‘Integrating Sphere Theory & Application’ and ‘Integrating Sphere Radiometry & Photometry’ from the Pro-Lite web site (www.pro-lite.uk.com).

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Robert Yeo is a founding partner in Pro-Lite Technology LLP (Cranfield, UK, www.pro-lite.co.uk), a specialist distributor of photonics products and equipment used for optical radiation measurements. Pro-Lite serves as the exclusive distributor for Labsphere Inc in the United Kingdom and Republic of Ireland.