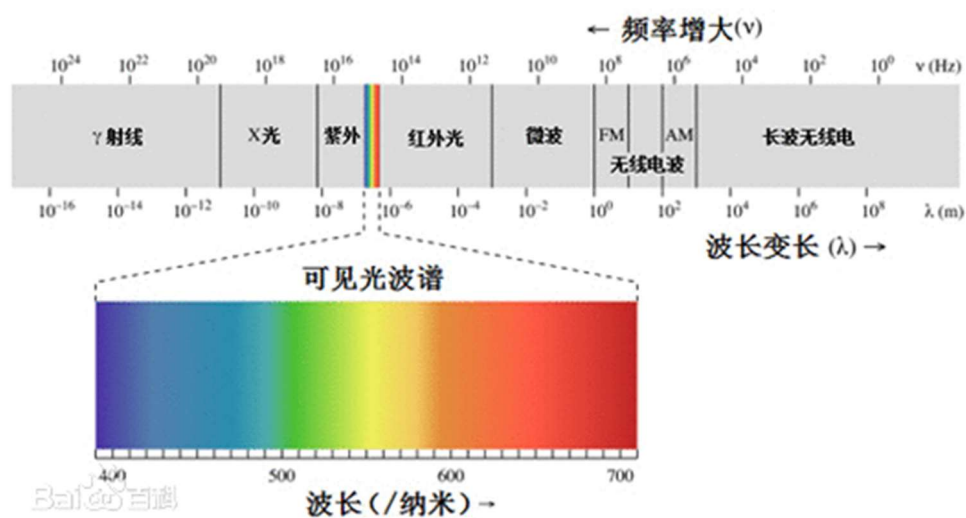


Integrating Sphere Principle and Applications

1. Basic Photometry Knowledge

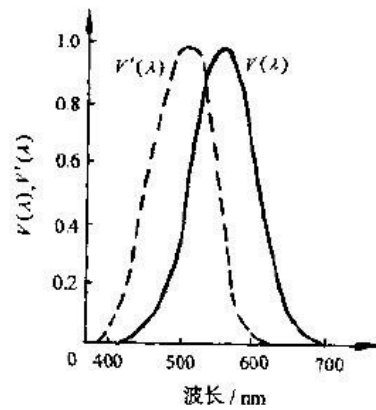
1.1 Electromagnetic Waves (EM Waves)

Also known as electromagnetic radiation. The range of electromagnetic radiation that human eyes can perceive is known as visible light, approximately between 380nm to 780nm.



1.2 Luminous Efficiency Function (Visual Function)

This represents the human eye's sensitivity to different wavelengths of light. It is divided into photopic vision function $V(\lambda)$ for bright conditions and scotopic vision function $V(\lambda')$ for dark conditions.



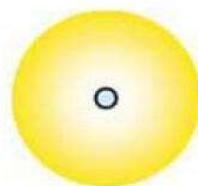
$V(\lambda)$ 和 $V'(\lambda)$
函数曲线

1.3 Radiant Flux (Φ_e)

The energy emitted, transmitted, or received in the form of electromagnetic radiation per unit time is called radiant flux, measured in watts (W).

1.4 Luminous Flux (Φ)

The product of the radiant flux within the visible spectrum and the relative visual function, measured in lumens (lm).



光通量

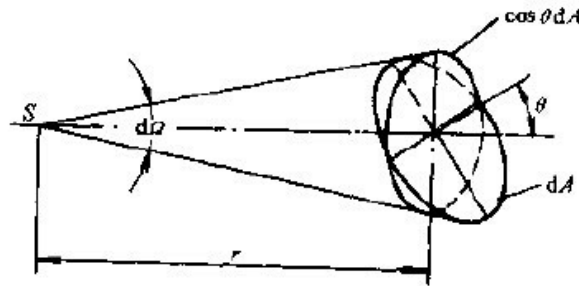
1.5 Illuminance (E)

The luminous flux received per unit area, defined as the illuminance on a surface, measured in lumens per square meter (lm/m^2).

$$E = \frac{\Phi}{S}$$

1.6 Solid Angle (Ω)

The three-dimensional space enclosed by a conical surface is known as a solid angle. It's particularly relevant in describing the directional spread of light from point sources.



Equation:

$$\Omega = \frac{dA}{r^2}$$

1.7 Luminous Intensity (I)

The visible light emitted by a point source in a particular direction, measured as the luminous flux per unit solid angle, measured in candela (cd).



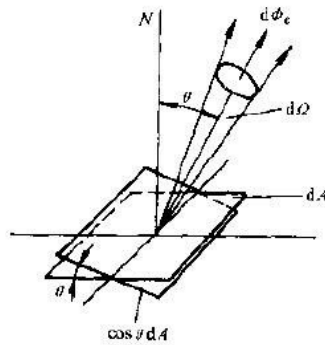
Equation:

$$I = \frac{\Phi}{\Omega}$$

1.8 Luminance (L)

The luminous flux per unit area per unit solid angle in a given direction, defining the brightness of a light source, measured in candela per square meter

(cd/m²).



亮度定义中
各量的示意图

Equation:

$$L = \frac{d\Phi}{\cos \theta dA d\Omega} = \frac{dI}{\cos \theta dA}$$

1. Principle and Application of Integrating Sphere

2.1 Function and Application of Integrating Sphere

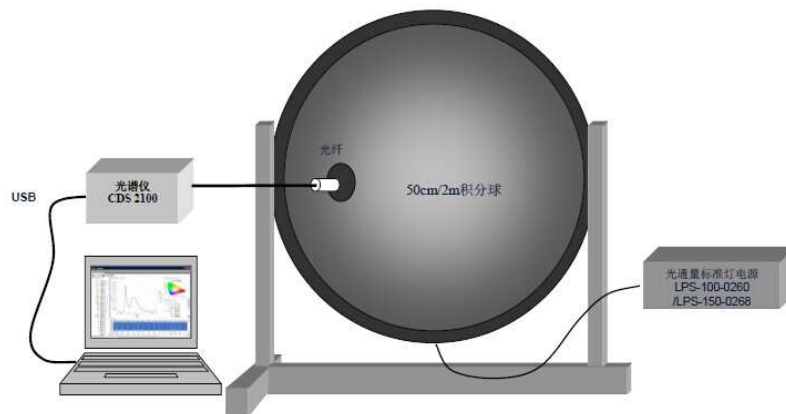
The primary function of an integrating sphere system is to measure the radiometric, photometric, and colorimetric parameters of light sources, including luminous flux, illuminance, color temperature, chromaticity coordinates, luminous efficacy, etc. Integrating spheres are mainly used in the field of light source and luminaire photometry.



An integrating sphere is a hollow spherical structure internally coated with a diffuse reflective coating and typically made of metal with several small openings. Inside the sphere, there are

standard lamps, auxiliary lamps, fiber interfaces, etc., while externally connected

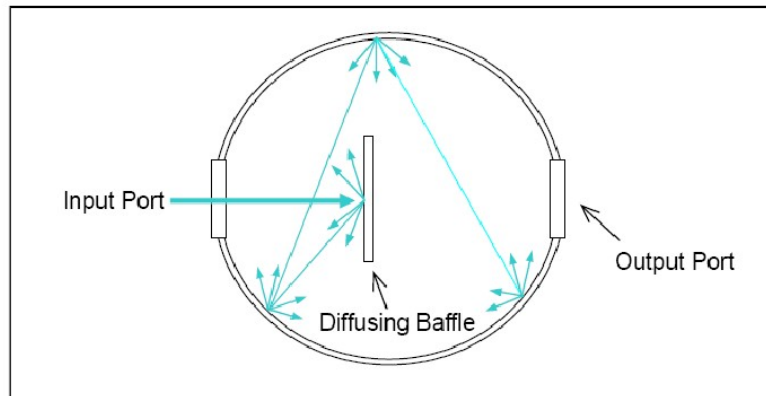
devices include power supplies, computers, spectrometers, and other instruments.



2.2 Ideal Integrating Sphere System

1. The interior surface should be a perfect sphere with consistent radius.
2. The inner walls should have a uniform diffuse reflective coating, exhibiting the same diffuse reflectance for all wavelengths.
3. The sphere should be devoid of any objects, and the light source should be considered an abstract source without physical presence.

2.3 Basic Working Principle of Integrating Sphere



As illustrated, when light enters through an input port, it is uniformly reflected and diffused inside the sphere. Thus, the light exiting the sphere through the output port is a uniform diffuse beam. The incident angle, spatial distribution, and polarization of the incident light do not affect the intensity and uniformity of the output beam. Also, as light integrates within the sphere before exiting, the integrating sphere can act as a light intensity attenuator. The ratio of output intensity to input intensity is approximately the area of the output port to the interior surface area of the sphere.

2.5 Lambertian Source and Lambertian Properties

If the luminous intensity of a light source varies according to the cosine law, meaning its brightness is independent of direction, such an emitter is referred to as a cosine emitter or Lambertian body. Lambertian light sources are also known as cosine bodies.

Lambertian property: The brightness of the light emitted from the source appears the same from any direction.

Natural Lambert bodies: include the sun, frosted glass lampshades, white paper, snow, and white walls.

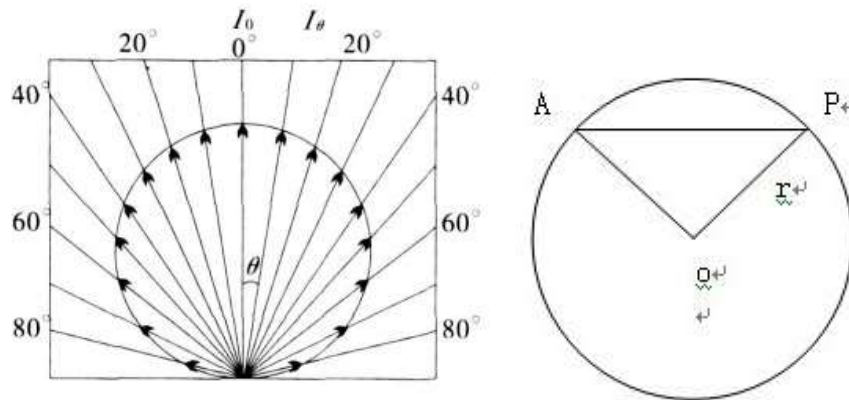


图 1 朗伯光源 $I_{\theta} = I_0 \cos \theta$

According to the previous definition of brightness, it is understood:

$$L = \frac{I}{\cos \theta \cdot A}$$

When the luminous intensity of a light source satisfies:

$$I = I_0 \cos \theta$$

The brightness of the light source is independent of direction.

According to Lambert's law, this explains the principle of the integrating sphere:

As shown in the figure, O is the center of the sphere, and r is the radius. A is a diffuse reflection source on the sphere surface with a unit area of dS, and the light flux of the light source is Φ . The illuminance at point P:

$$E_p = \frac{d\Phi}{dS}$$

Considering the diffuse reflection of the entire emitting surface, the illuminance at point P is:

$$E_p = \frac{\Phi}{4\pi r^2}$$

Assuming the coating's diffuse reflection coefficient is ρ . Assuming a light

flux of Φ is incident inside the integrating sphere, forming uniform light inside. At any point A inside the sphere, the illuminance is E, and E_0 is the illuminance produced by the first reflection (considering the effect of the baffle on the light source):

$$E_0 = \rho \frac{\Phi}{4\pi r^2}$$

This light will undergo infinitely many reflections inside the sphere. The total illuminance at point A after n reflections:

$$E = \rho \frac{\Phi}{4\pi r^2} + \rho^2 \frac{\Phi}{4\pi r^2} + \dots + \rho^{n+1} \frac{\Phi}{4\pi r^2}$$

When $\rho < 1$, $n \rightarrow \infty$

Conclusion:

$$E = \frac{\rho}{1 - \rho} \cdot \frac{\Phi}{4\pi r^2}$$

Since the reflectivity ρ is related to the wavelength λ , in engineering practice, it is generally:

$$\tau(\lambda) = \frac{\rho(\lambda)}{1 - \rho(\lambda)}$$

And this is used as an index to evaluate the integrating sphere.

The illuminance inside the integrating sphere is related to the coating's diffuse reflection, light flux, and the radius of the sphere. If we require uniform illuminance, we need to ensure the integrating sphere coating has stable diffuse reflectivity, and the sphere radius is consistently equal.

When the light inside the integrating sphere is uniform, we can measure the illuminance E at any point. According to the principle of irradiance:

$$E = \frac{\Phi(\lambda)}{S}$$

The light flux $\Phi = (\lambda)$ corresponding to a certain spectrum can be calculated, then the light flux of the light source:

$$\Phi = K_m \int \Phi(\lambda) \cdot V(\lambda) d\lambda$$

Where $K_m = 683 \text{lm/W}$, $V(\lambda)$ is the visual function.

2. Integrating Sphere Coating

3.1 Integrating Sphere Coating

1. The quality of an integrating sphere mainly relies on the coating, baffle, opening, and the perfection of the sphere, with the coating being the most important.
2. The main difference between domestic and foreign integrating spheres is the different coatings used.

3.2 Conditions Required for Integrating Sphere Coating

1. According to CIE standards, the diffuse reflectance rate should be at least 80%.
2. The diffuse reflectance rate should change little with wavelength, i.e., show spectrally neutral characteristics.
3. Good chemical stability, no yellowing.

(About the standard requirements of integrating sphere coating: CIE-84-1989)

Measurement of Luminous Flux)

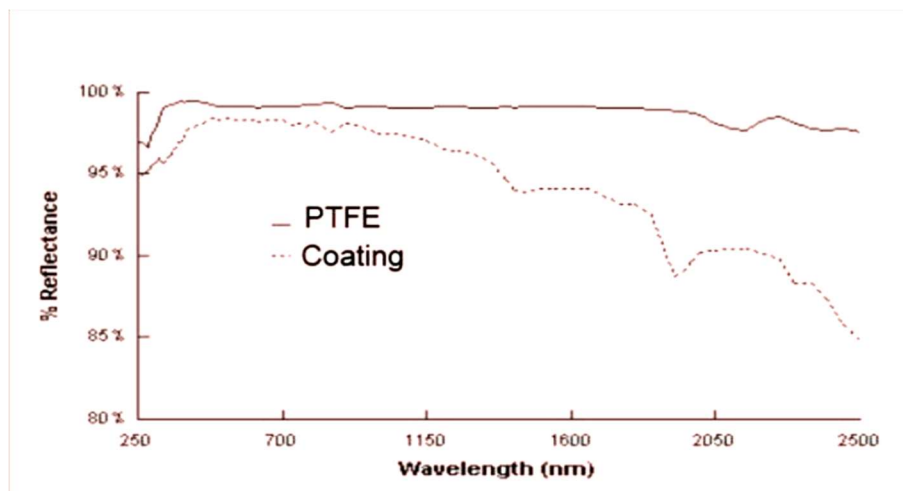
3.3 Common Integrating Sphere Coatings

Integrating spheres have many coatings, and different coatings are suitable for different wavelength ranges. Integrating sphere coatings are critical, with

manufacturers generally using barium sulfate (BaSO_4),
polytetrafluoroethylene (PTFE), etc., as integrating sphere coatings.

In terms of coatings, domestically lower-end ones mainly use magnesium oxide (MgO), barium sulfate (BaSO_4), and the higher-end ones use domestically produced polytetrafluoroethylene suspension resin (PTFE).

PTFE replaces the commonly used magnesium oxide (MgO) and barium sulfate (BaSO_4) as the integrating sphere coating. Within the 0.2~2.5 micrometer wavelength range, the spectral reflectance ratio is higher than that of MgO and BaSO_4 , and the reflectance ratio is neutral, which is beneficial in reducing its impact on the non-neutrality of the integrating sphere. In addition, the coating is sticky and not easy to crack or wrinkle. Dust can be removed with a clean brush without damaging the coating. PTFE coating is not afraid of humidity, nor will it turn yellow when exposed to ultraviolet light.

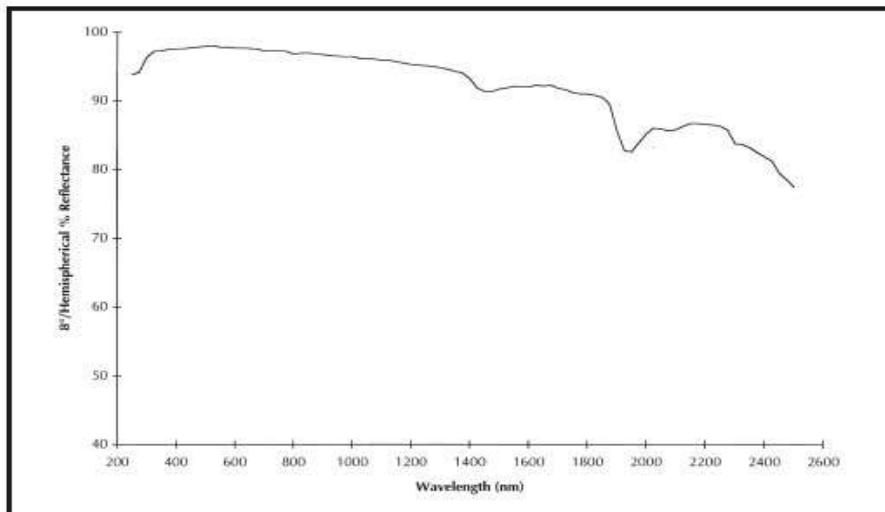


Comparison chart of reflectance between polytetrafluoroethylene and barium sulfate

Abroad, different coatings are used for different scenarios. For waterproof, moisture-proof, and corrosion-resistant, there is Duraflect; for working in near and mid-infrared bands, there is Infragold; for working simultaneously in ultraviolet, visible, and near-infrared bands with high reflectivity, there is Spectralon.

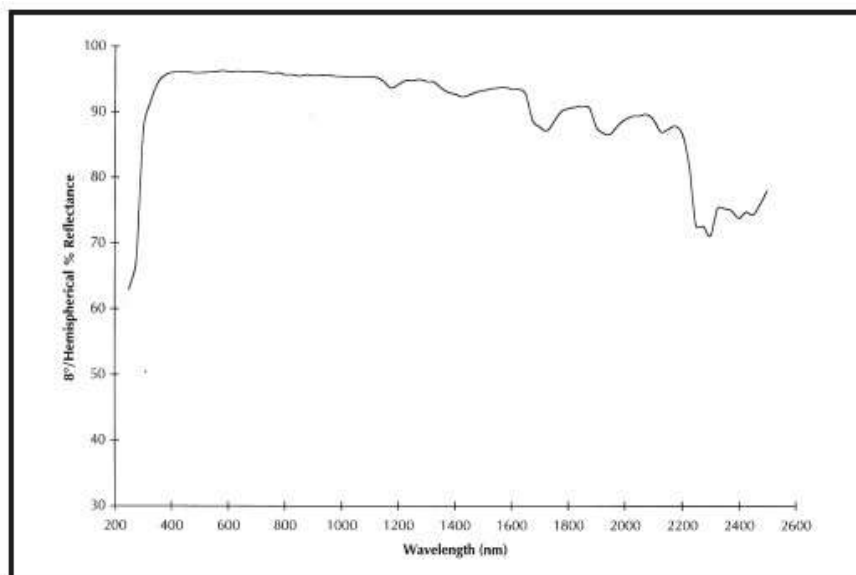
3.3.1 Spectralect Coating

Economical and practical with high reflectance in the visible spectrum. Above 0.5mm thickness, between 400-1100nm, the reflectance exceeds 99%. Provides 97% reflectance in the 360-830nm spectrum range and can extend to the 300-2400nm range.



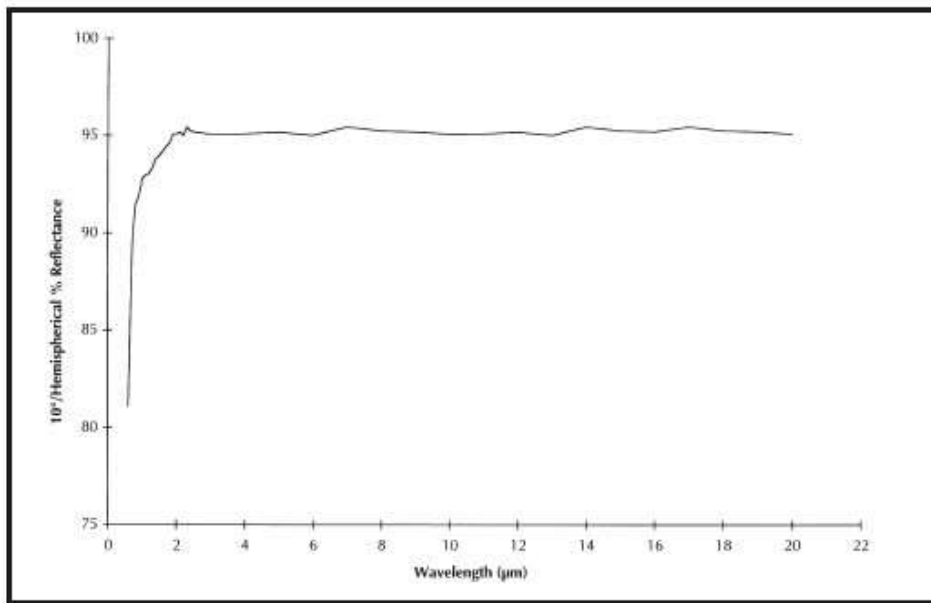
3.3.2 Duraflect Coating

Reflectance exceeds 95% between 350-1200nm. Its main advantages are waterproof, moisture-proof, and corrosion-resistant. Suitable for harsh environments such as weathering, wear, and humidity conditions.



3.3.3 Infragold Coating

Works in near, mid, and far-infrared bands, exhibiting excellent performance in the infrared range from 700nm to 2000nm. Mainly used for optical measurement of low-power lasers.



3.3.5 Comparison of Diffuse Reflectance of Integrating Sphere Coatings Domestically and Internationally

材料	反射率	紫外光	可见光	近红外光
	波长(nm)			
XX光学 SPEKTRON		/	0.8	/
硫酸钡涂料 R80		/	0.8	/
经济型硫酸钡 R93		/	0.93	/
高反射率硫酸钡涂料 R98		0.93	/	/
		/	0.985	0.985
聚四氟乙烯(PTFE)		0.95	0.97	0.97
Spectrafect		0.94	0.97	0.93
Duraflect		/	0.96	0.93
Infragold		/	/	0.9
Spectralon		0.96	0.99	0.99

3. Measurement with an Integrating Sphere

The electrical and photometric measurement standards for solid-state lighting products, LM-79-80, specify the measuring methods for integrating

spheres. The luminous flux measurement in an integrating sphere must be based on calibration. The light flux of the test lamp is obtained by comparison with a standard lamp, reducing measurement errors. The role of the auxiliary lamp is to compare the differences in light absorption due to the shape or color of the standard and test lamps.

4.1 Total Luminous Flux Measurement (4π measurement)

In this design, the test source is placed inside the integrating sphere to capture all the light emitted from it. With a properly calibrated system, this geometry can provide very precise measurement results.

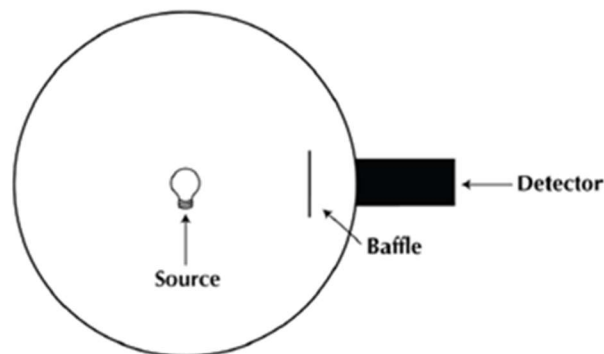


FIGURE 1.2

4.2 Point Light Source (2π measurement)

Some light sources, such as lasers, have strong directionality and can be introduced into the integrating sphere through the entrance port of the sphere (Figure 1.3). This detection method has several advantages. Firstly, the integrating sphere eliminates the need for precise alignment of the laser beam. Secondly, it removes the effects of non-uniform detector response. Thirdly, the

sphere naturally attenuates the energy from the laser, allowing the use of faster, more sensitive detectors.

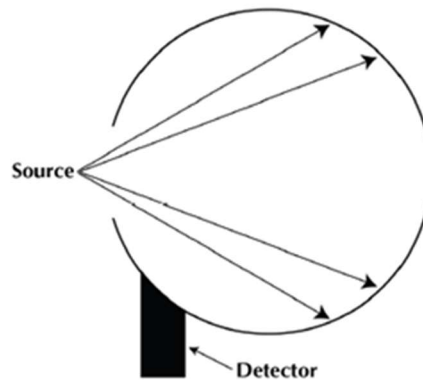


FIGURE 1.3

4.3 Integrating Sphere Attenuation Coefficient f

Where d is the diameter of the exit port and D is the diameter of the integrating sphere. Specific values can be calculated as needed, and the table provides simple queries for some $d:D$ situations.

Table 1. $f = \frac{1}{2} \{1 - [1 - (d/D)^2]^{1/2}\}$

d/D	f	d/D	f
0.00	0.000000	0.45	0.05349
0.025	0.0001563	0.50	0.06699
$1/24$	0.0004342	0.55	0.08242
0.05	0.0006254	0.60	0.1000
$1/16$	0.0009775	$5/8$	0.1096
0.075	0.001408	0.65	0.1200
$1/12$	0.001739	$2/3$	0.1273
0.10	0.002504	0.70	0.1429
$3/24$	0.003922	0.75	0.1693
0.15	0.005657	0.80	0.2000
$1/6$	0.006993	$5/6$	0.2236
$3/18$	0.008868	0.85	0.2366
0.20	0.01010	0.90	0.2821
$5/24$	0.01097	0.95	0.3439
0.25	0.01588	1.00	0.5000
0.30	0.02303		
$5/18$	0.02504		
$1/3$	0.02860		
0.35	0.03163		
$3/8$	0.03649		
0.40	0.04174		
$5/12$	0.04547		

4.4 Integrating Sphere Transmittance

$$R \cdot A_p / \{A_s \cdot [1 - R(1 - f)]\}$$

Where R is the internal surface reflectance of the integrating sphere; A_p is the effective measurement area of the probe; A_s is the internal surface area of the integrating sphere; F is the proportion of the non-reflective area to the entire internal surface.

4.5 Basic Operation Steps of a General Integrating Sphere

1. Place the standard lamp inside the integrating sphere, turn it on, and get the spectrometer reading $y_{REF}(\lambda)$.
2. Turn off the standard lamp, turn on the auxiliary lamp, and get the spectrometer reading $y_{aux,REF}(\lambda)$.
3. Don't turn off the auxiliary lamp, replace the standard lamp with the test

lamp (don't turn on the test lamp), and get the spectrometer reading $y_{aux,TEST}(\lambda)$.

4. Turn off the auxiliary lamp, turn on the test lamp, and get the spectrometer reading $y_{TEST}(\lambda)$.

4.64.6 Calculating Formula for Integrating Sphere

$$\Phi_{TEST}(\lambda) = \Phi_{REF}(\lambda) \cdot \frac{y_{TEST}(\lambda)}{y_{REF}(\lambda)} \cdot \frac{1}{\alpha(\lambda)}$$

Where $\alpha(\lambda)$ is the self-absorption compensation coefficient and $\Phi_{TEST}(\lambda)$ is the spectral radiance of the test lamp for each wavelength. Using the following formula, you can calculate the actual luminous flux of the test lamp:

$$\alpha(\lambda) = \frac{y_{aux,TEST}(\lambda)}{y_{aux,REF}(\lambda)}$$

$$\Phi_{TEST} = K_m \int_{\lambda} \Phi_{TEST}(\lambda) V(\lambda) d\lambda$$

($K_m = 683 \text{ lm/W}$)

Where K_m is the maximum spectral luminous efficacy function.

4.7 Spectral Luminous Efficacy $K(\lambda)$

$$K(\lambda) = \Phi_v(\lambda) / \Phi_e(\lambda) = K_m \cdot V(\lambda)$$

It describes the luminous flux produced by monochromatic light radiation flux at a wavelength λ , i.e., the ratio of monochromatic light flux $\Phi_v(\lambda)$ to monochromatic light radiation flux $\Phi_e(\lambda)$ is defined as spectral luminous efficacy. $K(\lambda)$ represents the photopic spectral luminous efficacy, and $K'(\lambda)$

represents the scotopic spectral luminous efficacy, measured in lm/W. K_m is the maximum spectral luminous efficacy, i.e.:

- Photopic vision $K_m = K(555) = 683 \text{ lm/W}$
- Scotopic vision $K'_m = K'(507) = 1700 \text{ lm/W}$

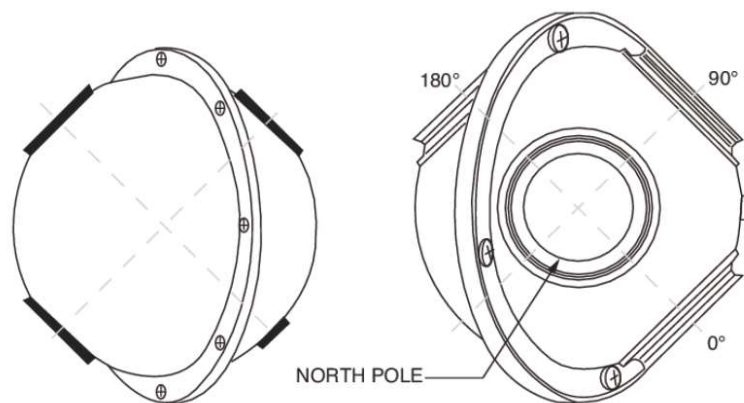
4.7 Laser Power/Transmission and Reflection Integrating Sphere $K(\lambda)$

$$K(\lambda) = \Phi_v(\lambda) / \Phi_e(\lambda) = K_m \cdot V(\lambda)$$

5. Laser Power/Transmission and Reflection Integrating Sphere

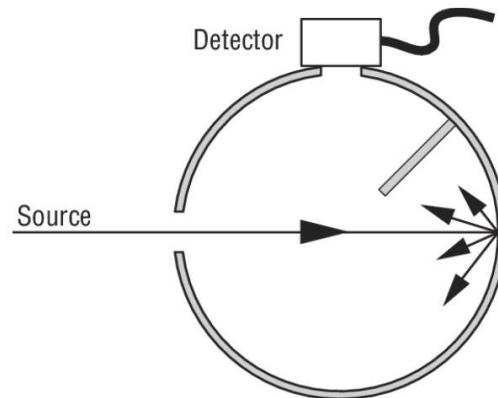
5.1 Collimated Beam Integrating Sphere

Ideal integrating sphere for collimated beams: When choosing the right integrating sphere, consider your application. Sphere ports increase the functionality of the integrating sphere but also reduce the uniformity of light distribution inside the sphere. A 4-port integrating sphere, with ports located at 0 degrees, 90 degrees, 180 degrees, and the polar position, ranges between 2 inches and 6 inches. Baffles are located between the 0-degree and 90-degree ports. Note that some integrating spheres come with a 0-degree port plug.



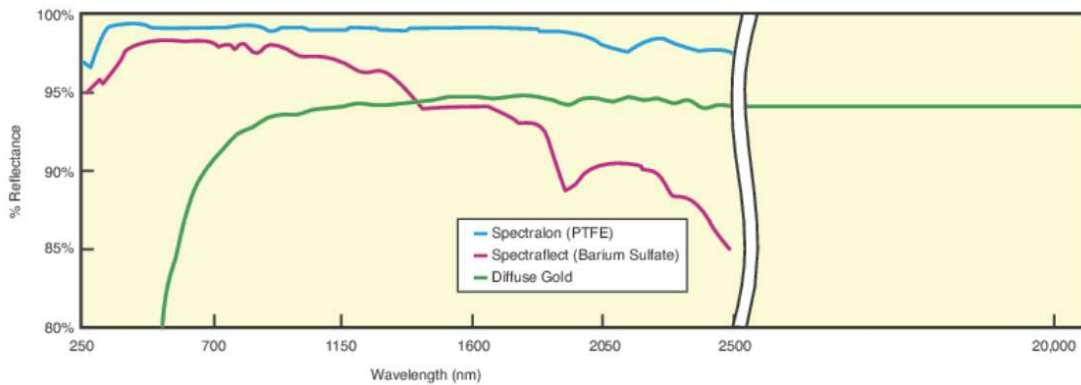
5.1.1 Applications of Integrating Sphere

LiSen Optics integrating spheres are particularly suitable for applications requiring a 180° port. Detectors are usually mounted on the 90° port, while the source light beam can enter the sphere through the 0° or 180° port, depending on the application. Common applications include measuring the total power of collimated laser beams (including fiber-collimated outputs), measuring transmitted radiation from irradiated samples, and measuring reflected radiation from irradiated samples.



5.1.2 Reflectance of Integrating Sphere

Based on the high reflectance integrating sphere with hydrophobic, chemically inert properties, and thermal stability up to 350°C, it can be used in more demanding environments, including underwater, high temperature, or low temperature processes. Meanwhile, with reflectance over 95% in the 250–2500 nm range, over 98% in the 310–2100 nm range, and over 99% in the 400–1500 nm range, they are ideal for the most demanding measurements from ultraviolet to near-infrared.



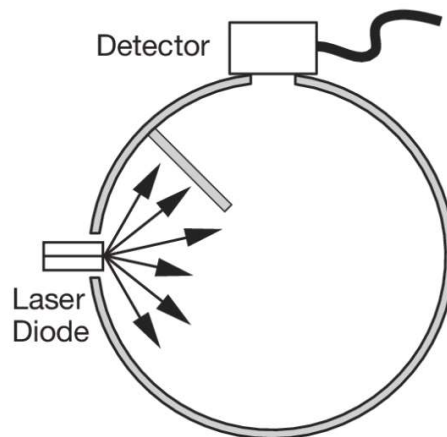
5.1.3 Choosing Integrating Sphere Size

The physical limitations of the measurement system are a factor in choosing the size of the integrating sphere. Generally, as the diameter of the sphere increases, its "integrating" properties improve, port sizes can be larger, and it can accommodate higher input powers. However, as the system attenuation increases, throughput decreases.

5.2 Diverging Beam Integrating Sphere

5.2.1 Diverging and Collimated Beam Input

Based on the beam divergence characteristics of the light source, LiSen Optics offers two different types of spherical probes. LiSen Optics optical integrating spheres are used for diverging light sources and collimated input beams. In the LiSen Optics optical integrating sphere series, a baffle is located between the input port and the probe to prevent undiffused beams from directly illuminating the probe. When measuring collimated beams, the baffle should be positioned so that the beam is not directly illuminated on the probe after the first reflection inside the sphere.



5.2.2 Why Use Integrating Sphere Power Probes for Lasers?

One of the main advantages of using an integrating sphere is the diffusion of input beams, making the probe readings unaffected by errors caused by probe positioning, problems related to overfilling, and saturation of the probe's effective area. The probe should see a completely diffused input field. Therefore, a key technical consideration when deciding which configuration to choose is whether the input beam will directly illuminate the probe, affecting the probe's optical power. Therefore, each integrating sphere contains a baffle.

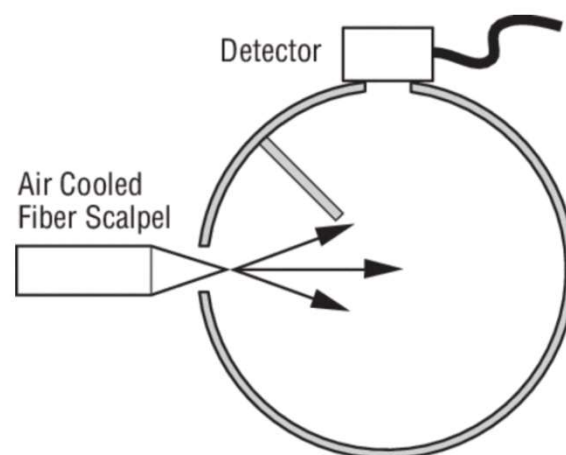
5.2.3 Accuracy of Traceable Calibration

Calibrated integrating sphere probes are supplied with a low noise silicon, UV-enhanced silicon, or InGaAs photodiode. Integrating spheres with diameters of 2", 3.3", and 5.3" can be supplied. To maintain accuracy and ensure performance, LiSen Optics recommends annual calibration of the integrating sphere probes. Each product undergoes a full-spectrum response calibration using high-precision equipment installed in the LiSen Optics optical probe calibration facility. Strict calibration equipment and process control achieve the

strictest calibration uncertainties in the industry. Each probe comes with calibration data stored electronically in the detector's EEPROM. Each product comes with a calibration certificate, actual calibration curves, and data. To maintain accuracy and ensure performance, LiSen Optics recommends annual calibration of the photodiode probes.

5.3 Fiber Power Integrating Sphere

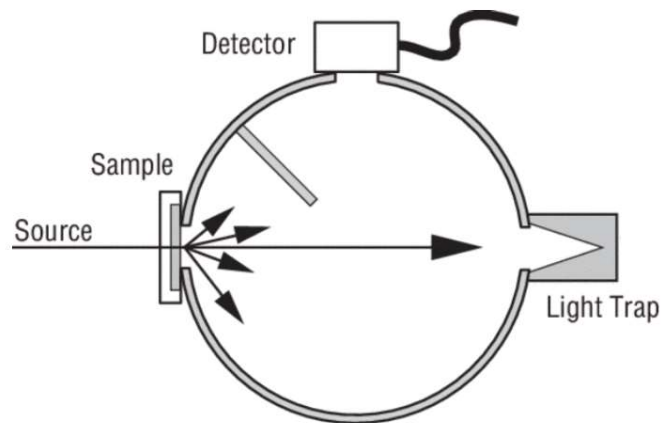
Integrating spheres are also ideal for measuring fiber output. Because the typical output of a fiber is slowly diverging, the first reflection point opposite the light source is not highly concentrated. Therefore, both collimated beam and diverging configurations are usually acceptable. However, if it's a light-guiding fiber, a diverging beam configuration is recommended due to the increase in NA. In cases of using fiber collimators, a collimated beam configuration is recommended.



5.4 Transmission Integrating Sphere

Transmittance can be measured using a 4-port integrating sphere to

collect the transmitted radiation from a sample at the 0-degree port. The sample is irradiated, then compared with direct light source measurements outside the sphere. A baffle is used to shield the detector from non-integrated transmission, and a light trap installed at the 180-degree port is used to remove unscattered components. Total integrated scattering, fluorescence, extrinsic scattering, and forward and backward scattering can also be measured. The detector is installed at the 90-degree port.



5.5 Reflection Integrating Sphere

To measure reflectance, the sample is fixed at the 0-degree port and illuminated by the incident light beam through the 180-degree port. The total reflected radiation is spatially integrated by the sphere and measured by a baffle detector. Using a normal incidence sample rack, the specular component of the reflected radiation can be eliminated by reflecting the specular beam back from the input port. An 8° incidence sample rack can measure "specular plus diffuse" reflectance. The reflectance of a sample relative to a known standard can be calculated by measuring both and taking their ratio. The

sample and standard should have similar reflectance to avoid errors caused by the sample's reflectance. A dual-beam system can be used to eliminate this potential source of measurement error. The detector is installed at the 90-degree port.

