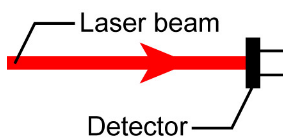
Absolute light power measurements using integrating sphere

Direct measurement of laser power using photo detector



The light output power of a laser is LP_L and the light power measured by photo detector is LP_D. It is

$$LP_D = LP_L . \qquad (1)$$

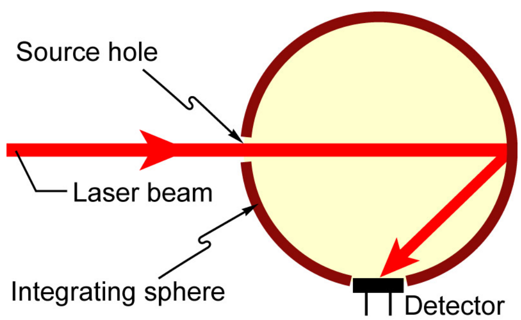
Indirect measurement of laser power using integrating sphere

Case (a) The integrating sphere perfectly reflects the light (R = 100 %), no optical loss occurs during the reflection.

The source hole through which the laser beam enters the sphere is assumed to be negligibly small.

The measured light power is given by:

$$LP_D = LP_L . \qquad (2)$$

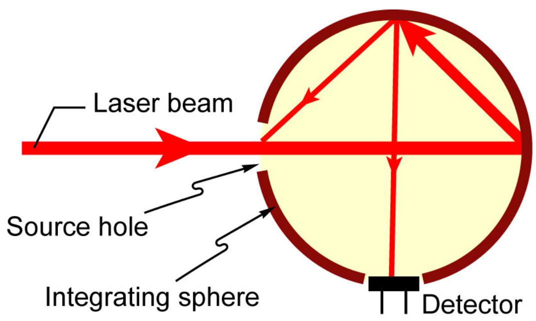


Case (b) The integrating sphere perfectly reflects the light (R = 100 %), no optical loss occurs during the reflection.

The loss due to the source hole is not neglected. We assume that the source hole area is equal to the detector hole area. Thus, the probability of a photon hitting the source hole and the detector hole is the same. Here we assume that the active area of the detector is larger than the detector hole area.

The measured light power is then given by:

$$LP_D = \frac{1}{2} LP_L . \tag{3}$$



Case (c) The reflectance of the integrating sphere is R with $R < 100$ %.

The loss due to the source hole is not neglected. The probability of a photon hitting the source hole, P_h, is equal to the ratio between the hole area and the integrating sphere surface area,

$$P_h = \frac{\text{area of the source hole}}{\text{surface area of the integrating sphere}} . \tag{4}$$

The probability of a photon hitting the detector, P_d, is equal to the ratio between the detector hole area and the integrating sphere surface area,

$$P_d = \frac{\text{area of the detector hole}}{\text{surface area of the integrating sphere}} . \tag{5}$$

The probability of a photon hitting the detector after the first reflection is given by

$$R\, P_d$$

The probability of a photon hitting the detector after the second reflection is given by

$$R\,(1 - P_d - P_h)\, R\, P_d$$

The probability of a photon hitting the detector after the third reflection is given by

$$[R\,(1 - P_d - P_h)]^2\, R\, P_d$$

Hence, the probability of a photon hitting the detector after the n-th reflection is given by

$$[R\,(1 - P_d - P_h)]^{n-1}\, R\, P_d$$

Let us assume that after n reflection events, the probability that a photon still exists in the integrating sphere, has decreased to 1/e. The corresponding expression is given by

$$[R(1 - P_d - P_h)]^n = \frac{1}{e} . \tag{6}$$

Solving this equation for n yields

$$n = \frac{-1}{\ln[R(1 - P_d - P_h)]} . \tag{7}$$

The total light power detected by the detector is

$$\begin{aligned} LP_D &= LP_L \left\{ R\, P_d \left[1 + R(1 - P_d - P_h) + R^2 (1 - P_d - P_h)^2 + \ldots \right] \right\} \\ &= LP_L \frac{R\, P_d}{1 - R(1 - P_d - P_h)} = LP_L / m^* \end{aligned} \tag{8}$$

where m^* is greater than 1.0 (i.e. $m^* >> 1$) and is given by

$$m^* = \frac{1 - R(1 - P_d - P_h)}{R\, P_d} . \tag{9}$$

Case (d) The area of the detector hole is larger than the active area of the photodetector. The reflectance of the integrating sphere is R with $R < 100$ %.

The probability of a photon hitting the source hole, P_h, and the detector hole, P_d, are given by Eqs. (4) and (5). The probability of a photon hitting the detector active area, P_{active}, is equal to the ratio between the detector active area and the integrating sphere surface area,

$$P_{active} = \frac{\text{active area of the detector}}{\text{surface area of the integrating sphere}} . \tag{10}$$

Equation (8) then becomes

$$\begin{aligned} LP_D &= LP_L \left\{ R\, P_{active} \left[1 + R(1 - P_d - P_h) + R^2 (1 - P_d - P_h)^2 + \ldots \right] \right\} \\ &= LP_L \frac{R\, P_{active}}{1 - R(1 - P_d - P_h)} = \frac{LP_L}{m^*\, m^{**}} \end{aligned} \tag{11}$$

where m^* and m^{**} are greater than 1.0 (i.e. $m^* >> 1$ and $m^{**} >> 1$). For $P_{active} \le P_d$, m^{**} is given by

$$m^{**} = \frac{P_d}{P_{active}} = \frac{\text{area of detector hole}}{\text{active area of detector}} \tag{12}$$

Example 1:

Let's assume $R = 1$, and $P_d = P_h$. We obtain

$$LP_D = \frac{1}{2} LP_L .$$

That's the situation of Case (b).

Example 2:

Let's assume that the radius of the sphere is 57.1 mm, the source hole diameter is 12.4 mm, the detector hole diameter is 17.3 mm, and $R = 99$ %. Then $P_d = 0.0057372$, $P_h = 0.0029475$, $n = 53$ and $m^* = 3.28$.

Example 3:

Using the setup described in example 2, let us now assume that the detector active area is $100 mm^2$, which is smaller than the area of the detector hole. Let us also assume that we are using a UV laser and the reflectance of the integrating sphere decreases to $R = 95\%$.

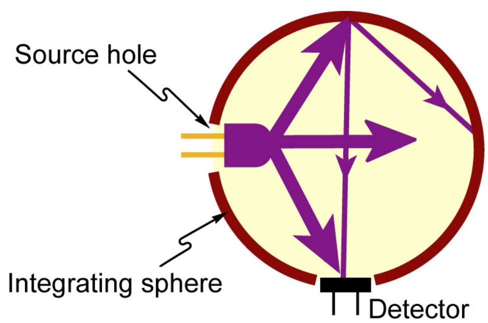
The values for P_d, P_h, and n remain the same where $P_d = 0.0057372$, $P_h = 0.0029475$, and $n = 53$. We find that $m^* = 10.7$ due to the reflectance change and $m^{**} = 2.35$ so that $m = m^* \times m^{**} = 25.1$.

Light output power measurement of LED using integrating sphere

Since we can measure the laser light output power by using both, the direct method and the indirect method, the prefactor m can be obtained from Eqs. (1) and (8). This prefactor is the *calibration* factor of the integrating sphere that we use when measuring the calibrated light output power of an LED.

The light output power of LEDs is given by

$$LP_{LED} = LP_D \frac{1 - R(1 - P_d - P_h)}{R P_d} = LP_D \times m^* m^{**} = LP_D \times m \quad . \qquad (13)$$

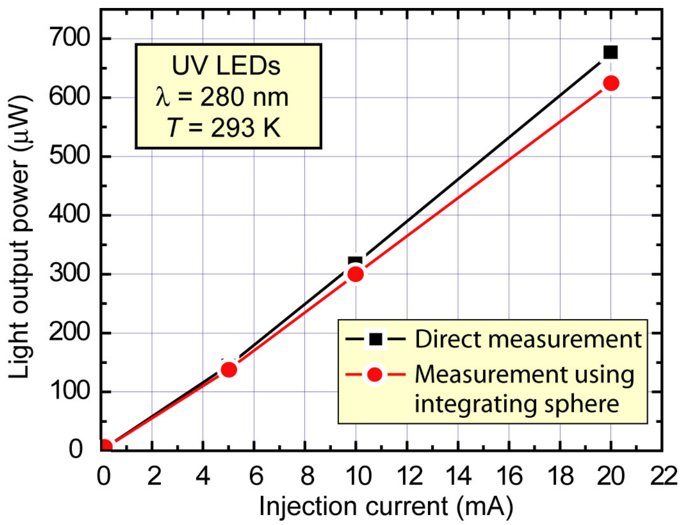


Note:

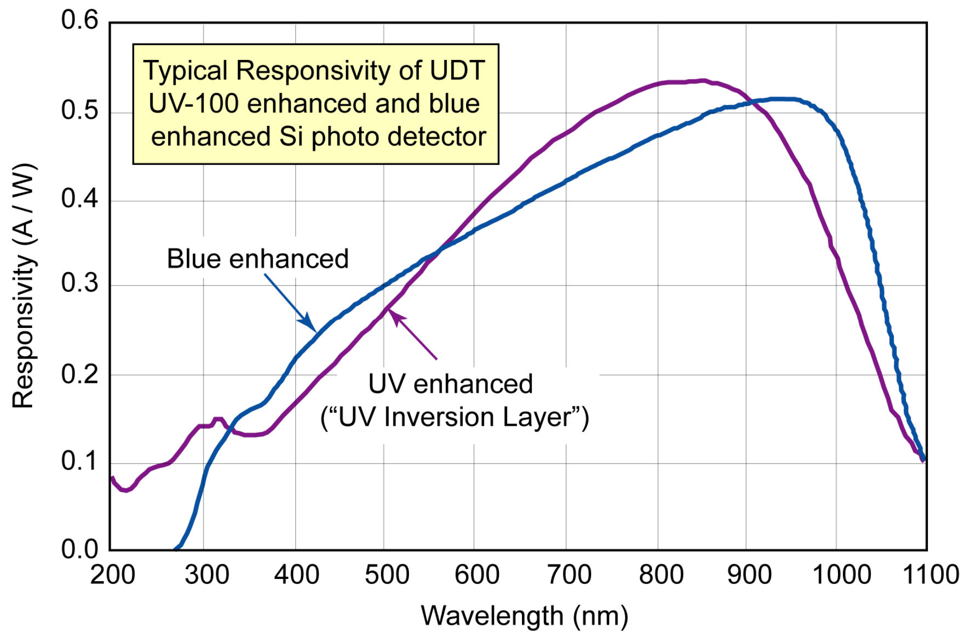
- m^* depends on λ.
- The detector responsivity (measured in A/W) is needed to convert the measured detector photocurrent to the corresponding light power.
- Any photodetector can be calibrated by using a calibrated optical power meter and the photodetector to measure the output power of a collimated laser beam.

Experimental results:

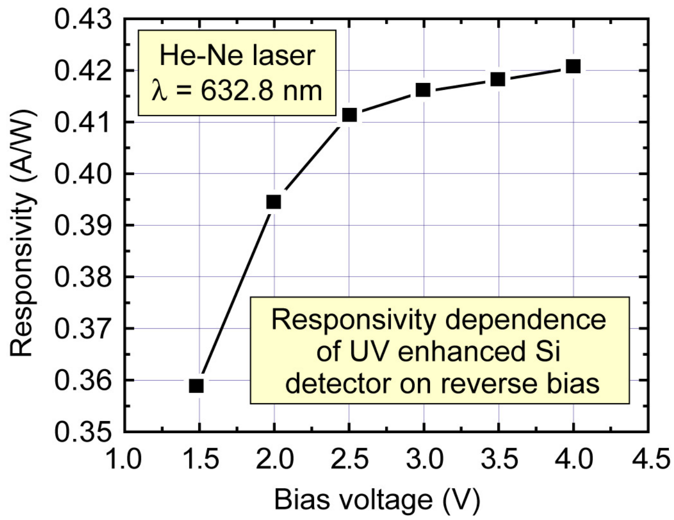
The figure below shows the difference in light output power using two different techniques. The direct measurement uses butt coupling of the UV LEDs to the Si photodetector to obtain the photo current and, using the detector responsivity, the optical power. Butt coupling of the UV LEDs in the flat-face package is assumed to have no optical loss (i.e. all light emitted by the LED impinges on the detector and no light leaks out). The same LED is then placed in the integrating sphere and the photocurrent is measured. Using the two measurements (butt coupling and integrating sphere) we can determine the calibration factor of m = 63.73. This calibration factor is then used for all integrating sphere measurements and a typical light output power versus injection current is shown below. Detailed experimental data are shown in the tables at the end of this teaching module.



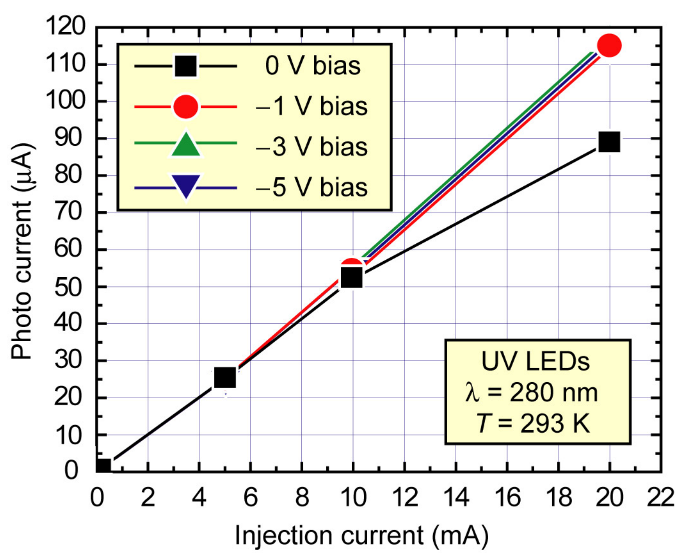
The following figure is the typical detector responsivity curve for the UDT UV-100 Si Photodetector given by the manufacturer (UDT Corporation). All the *reference responsivity values* ("reference value") given in the table are obtained from this figure.



We found a dependence of detector responsivity on reverse bias voltage for the detection of He-Ne 632.8 nm light. The figure below demonstrates the need for reverse biasing the UV detector when measuring He-Ne laser light at 632.8 nm.



For UV LEDs with peak wavelength 288 nm, the responsivity dependence upon bias is quite different from He-Ne laser case. The following figure shows the photocurrent dependence on injection current of UV LEDs under different bias conditions. At lower injection current, a limited number of electron-hole pairs are generated by the photons. All these electrons and holes are extracted out of the depletion region formed by the build-in electric field. Hence, applied bias won't affect the total photo current under low-intensity excitation. When the injection current of UV LEDs increases, more light will be absorbed by the UV detector, which means more electron-holes pairs are generated. Under certain conditions, the build-in electric field is not large enough to drag out all these electrons and holes. An applied voltage is needed. The figure just shows that at a 20 mA injection condition, the photocurrent increases from 89 μA to 116 μA when the bias increases from 0 V to –1 V. But since the light intensity is not as strong as the He-Ne laser, there is no difference for reverse biases beyond –1 V.



Wavelength 632.8nm using He-Ne laser and integrating sphere

Responsivity *R* (reference value) (*)	*R* = 0.43
Direct Ando Optical Power	430 μW
Directly Measured Photo Current (0 bias)	44 μA
Directly Measured Photo Current (– 4 V bias)	185 μA
Evaluated *R* with no reverse bias	*R* = 44/430 = 0.102
Evaluated *R* with – 4 Volt reverse bias	*R* = 185/430= 0.43
Measured Voltage across 1k ohm resistor	13 mV
Photodetector Current of UV LED	13 μA
Evaluated Optical Power	30.23 μW
Experimental *m* Factor	**430 μW/30.23 μW = 14.22**

Wavelength 488nm using Ar laser and integrating sphere

Responsivity *R* (reference value) (*)	*R* = 0.25
Direct Ando Optical Power	117 μW
Measured Voltage across 1k ohm resistor	1.77 mV
Photodetector Current of UV LED	1.77 μA
Evaluated Optical Power	7.08 μW
Experimental *m* Factor	**117 μW / 7.08 μW = 16.525**

Wavelength 280nm using a UV LED in integrating sphere

Responsivity *R* (reference value) (*)	*R* = 0.135
Direct Butt Coupling Optical Power	859.26 μW
Photodetector Current of UV LED	1.82 μA
Evaluated Optical Power	13.48 μW
Experimental *m* Factor	**859.26 μW / 13.48 μW = 63.73**

(*) UDT UV-100 Si Photodetector