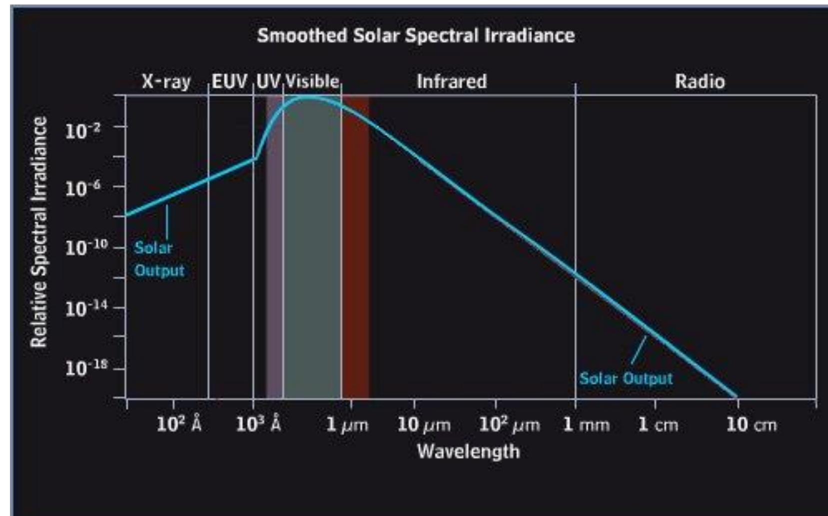
3. Radiometry and Photometry

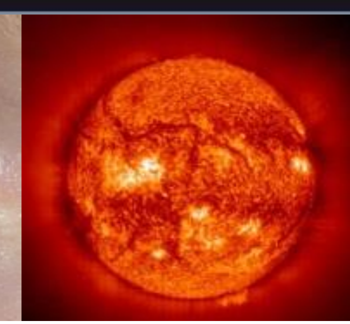
- **Radiometry**

  Measurement of the electromagnetic radiations within the wavelength range 0.01 - 1000 µm. (Physical approach)

- **Photometry**

  Measurement of the electromagnetic radiations weighted by the spectral response of the eye within the wavelength range 0.360 - 0.780 µm (visible light).

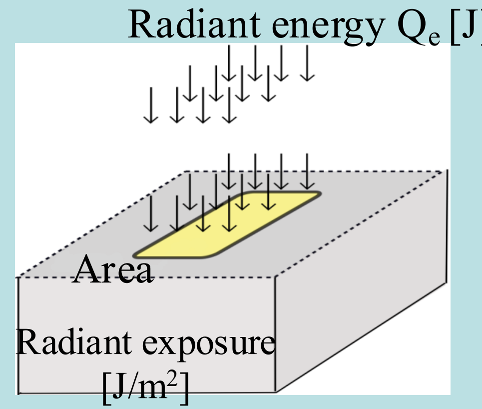




Unit systems - Overview

Radiometry			Photometry		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Energy	Q_e	J	Luminous Energy	Q_v	lm·s
Radiant Exposure	H_e	J·m^{-2}	Luminous exposure	H_v	lx s
Fluence	Ψ_e	J·m^{-2}	–	–	
Radiant Power Radiant Flux	ϕ_e	W	Luminous Flux	ϕ_v	lm or cd·sr
Fluence Rate	F_e	W·m^{-2}	–	–	
Emittance	M_e	W·m^{-2}	Luminous emittance	M_v	lm·m^{-2} or lux
Irradiance	E_e	W·m^{-2}	Illuminance	E_v	lm·m^{-2} or lux
Radiant Intensity	I_e	W·sr^{-1}	Luminous Intensity	I_v	cd
Radiance	L_e	W·sr^{-1}·m^{-2}	Luminance	L_v	cd·m^{-2}

Radiometry (Definition 1)



- Radiant energy: Q_e [J]

Energy transported by an electromagnetic radiation through the space.

- Spectral Radiant Energy: $Q_{e,\lambda}$ [J/nm]

Different emitting sources can have the same total amount of radiant energy but different emission spectra.

$$Q_{e,\,\lambda} = \frac{dQ_e}{d\lambda}$$

- Radiant Exposure: H_e [J/m²]

Energy Q_e [J] that reaches a surface of unit area.

$$H_e = \frac{dQ_e}{dA}$$

Radiometry (Definition 2)

- Radiant Power or Flux: ϕ_e [W]

Energy (Q_e) per unit time defines the radiant power or flux

$$\phi_e = \frac{dQ_e(t)}{dt} \xrightarrow{\phi_e = \text{const. } \forall\, t} \frac{Q_e}{\Delta t}$$

- Spectral Radiant Power: $\phi_{\mathrm{e},\lambda}$ [W/nm]

$$\phi_{\mathrm{e},\lambda} = \frac{d^2 Q_e(t,\lambda)}{dt\,d\lambda} = \frac{d\phi_e(\lambda)}{d\lambda} \xrightarrow{\phi_{\mathrm{e},\lambda} = \text{const. } \forall\, \lambda} \frac{\phi_e}{\Delta\lambda}$$

Radiometry (Definition 3)

- Irradiance E_e [W/m²]

  Emittance M_e [W/m²]

  Radiant flux per unit area :

  - reaching the surface A is called irradiance E_e

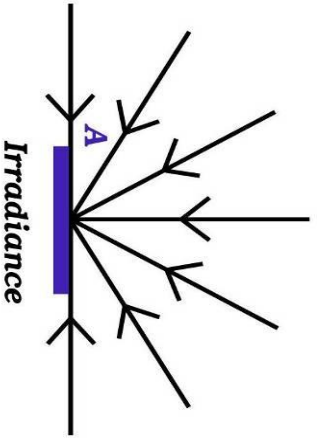
  - leaving the surface A is called emittance M_e

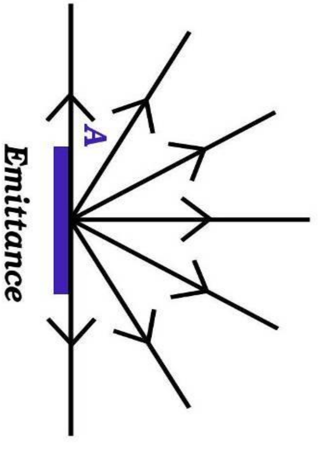
$$E_e = \frac{d\phi_e}{dA} \quad \text{and} \quad M_e = \frac{d\phi_e}{dA} \xrightarrow{E_e = \text{const. } \forall \text{ Surface}} \frac{\phi_e}{A}$$

- Spectral Radiant Flux Density:

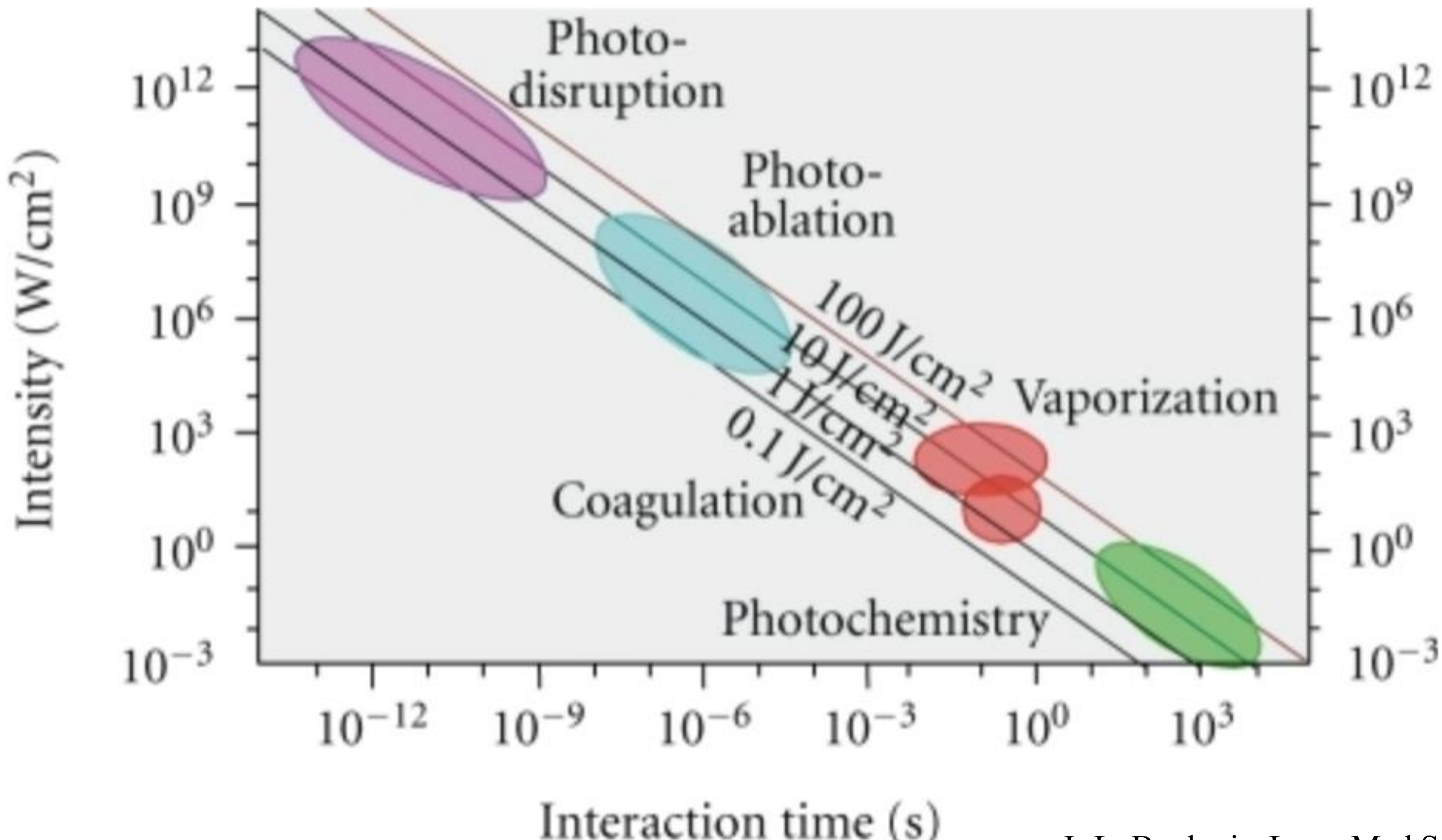
  $M_{e,\lambda}$ and $E_{e,\lambda}$ [W/(m² nm)]

$$E_{e,\lambda} = \frac{dE_e}{d\lambda} \text{ and } M_{e,\lambda} = \frac{dM_e}{d\lambda} \xrightarrow{E_{e,\lambda} = \text{ const. } \forall \lambda} \frac{E_e}{\Delta\lambda}$$





Light/laser tissue interactions: The tissue response strongly depends on the light irradiance (Intensity) !



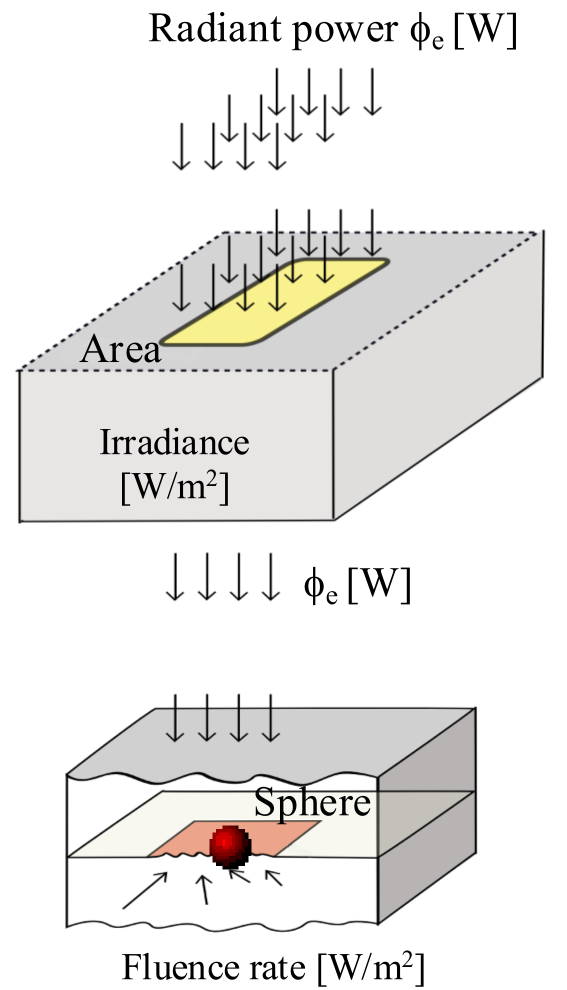
J.-L. Boulnois, Laser Med Sci, 1986

Radiometry (Definitions 4)

Irradiance vs. Fluence rate

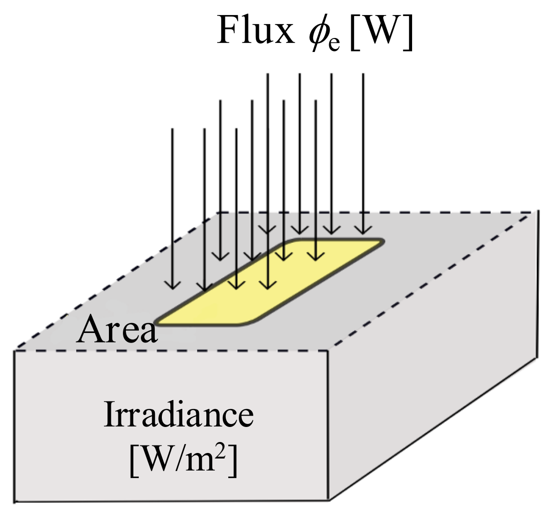
- Irradiance [W/m^2] describes the power per unit surface directly received from the source, whereas fluence rate [W/m^2] takes into account diffusion and scattering effects in the target environment.
- Fluence rate [W/m^2] is the Power entering a sphere presenting a unit cross-section.

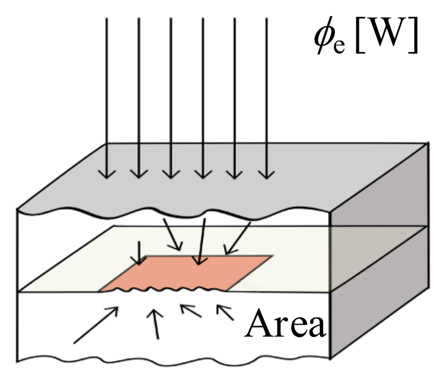
  The Fluence is of fundamental importance in dosimetry.



Radiometry (Note)

- Fluence rate [W/m^2] takes into account the direct flux as well as the scattering and diffusion contributions. Like the Fluence this term is of fundamental importance in dosimetry for photodynamic therapy and other laser techniques, where multiple scattering and diffusion in the target tissue are of great importance.
- It is important to note that the fluence rate and irradiance employ the same unit, W/m^2, but these are considerably different concept.
- Quantity measured with an isotropic power meter.

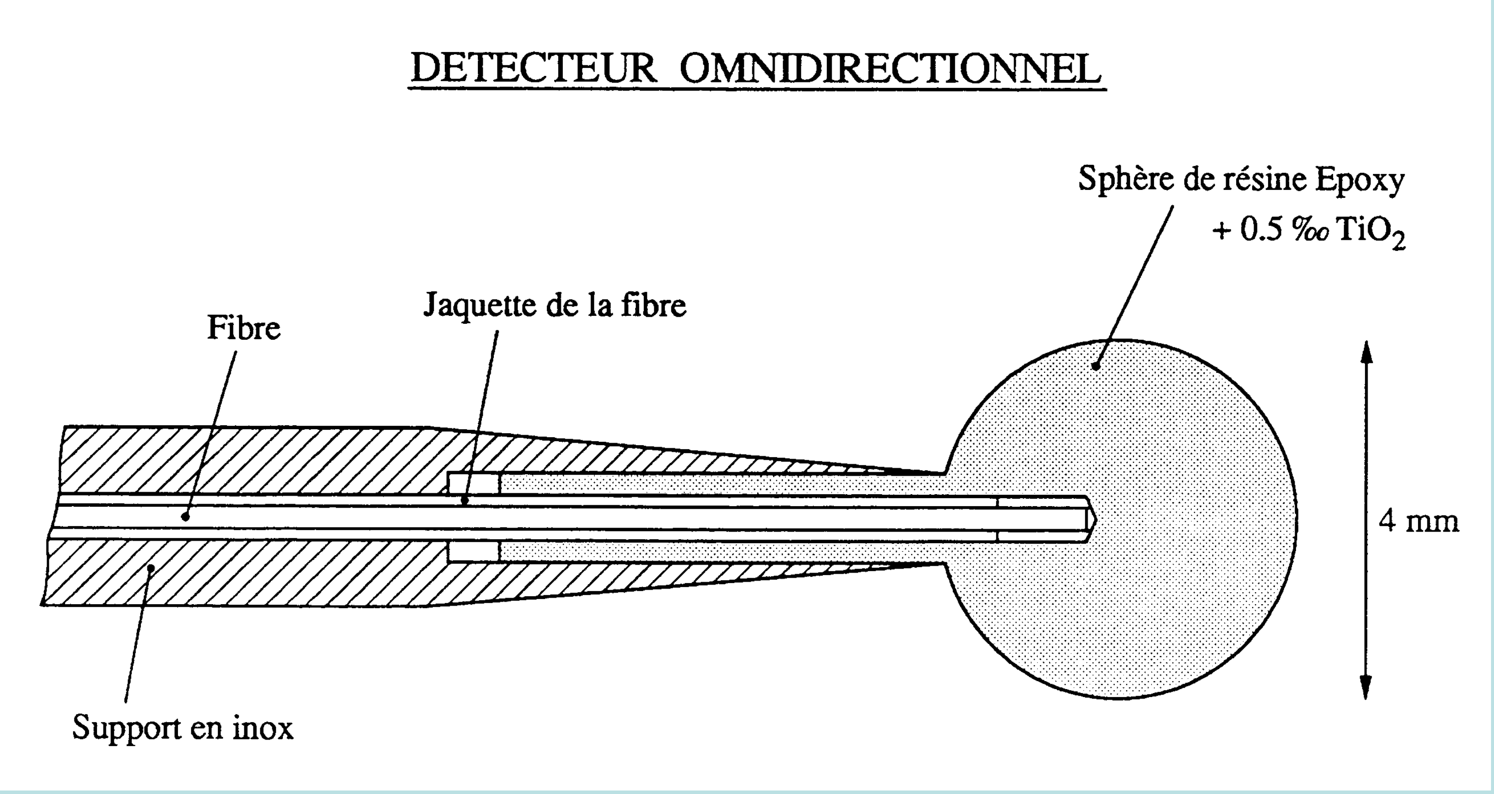




Fluence rate [W/m^2]

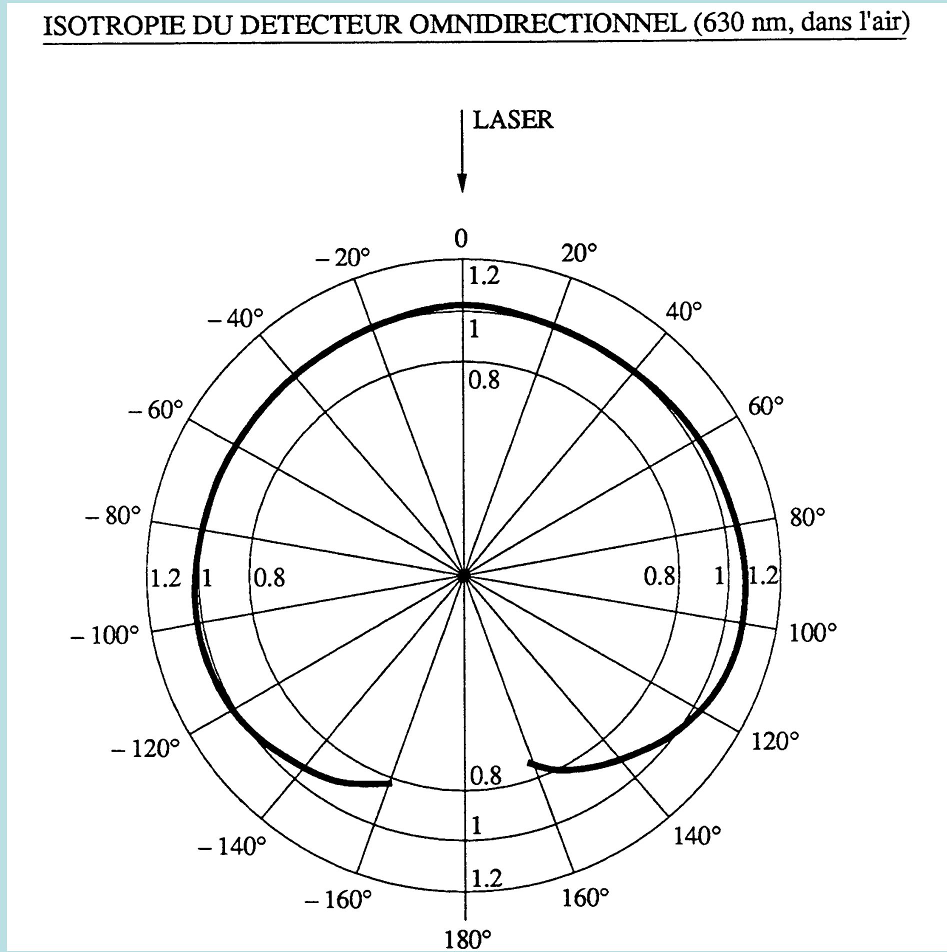
Measurement of the fluence rate with an isotropic detectors

Isotropic detector based on light scattering



Measurement of the fluence rate with an isotropic detector

Angular response of the isotropic detector

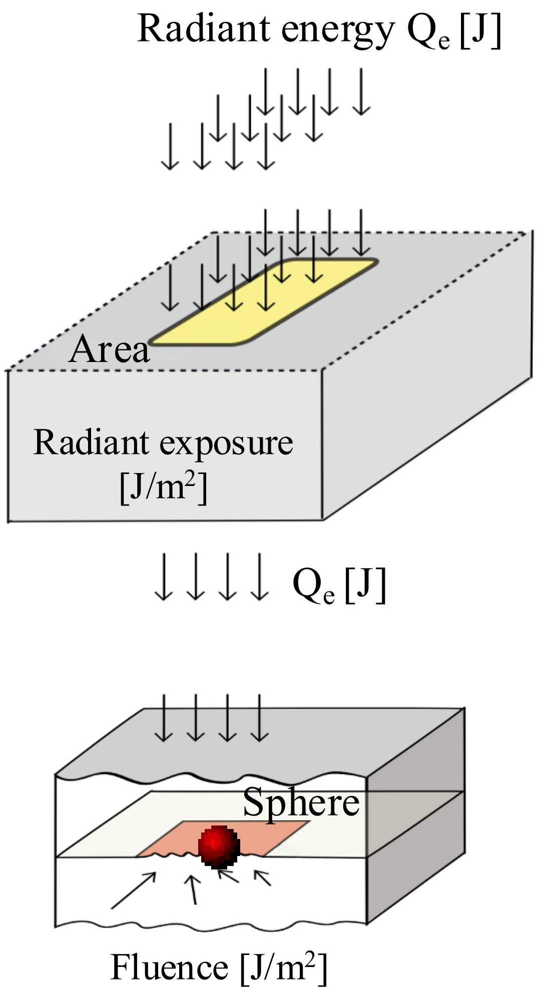


Radiometry (Definitions 5)

Radiant Exposure vs. Fluence

- Radiant Exposure [J/m²] describes the energy per unit surface <u>directly received from the source</u>, whereas fluence [J/m²] takes into account diffusion and scattering effects in the target environment.
- Fluence [J/m²] is the quantity measured with an isotropic power meter.

  (<u>Energy entering a sphere presenting a unit cross-section</u>)



Solid angle (Definition 6)

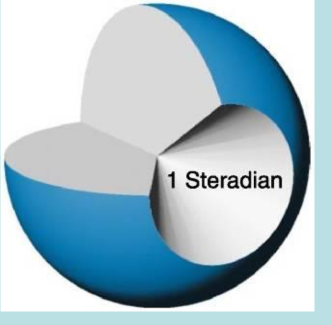
The quantities defined so far were omni directional, whereas radiant **intensity** and **radiance**, defined thereafter, characterize the propagation of a radiation in a specific direction.

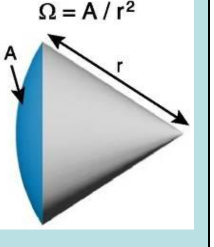
Solid Angle:

A solid angle is expressed in "steradian" [sr] (extended concept of radiant to the 3D). It is defined as the intersection area of a sphere and a cone which vertex stays in the sphere's center, divided by the square of the radius of the sphere.

$$\Omega = A / r^2$$

A sphere has a solid angle of $(4\pi r^2/r^2) = 4\pi$ [sr] which corresponds to a cone angle of π.





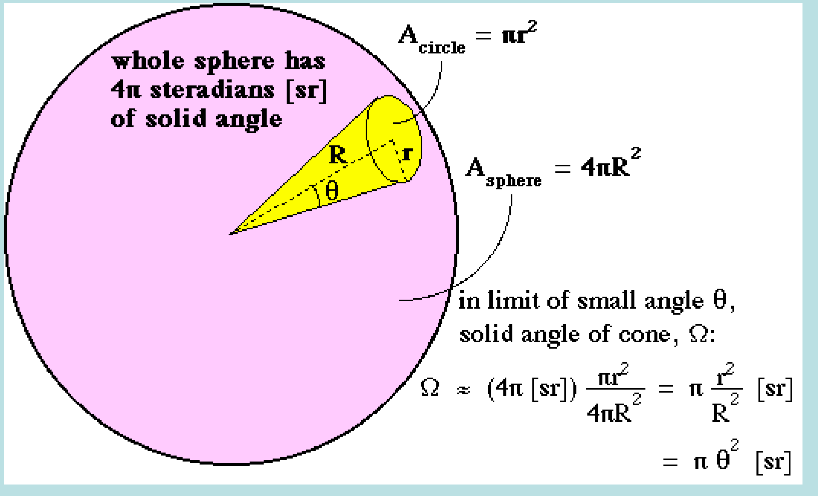
Solid angle (Note)

- Solid Angle Ω

$$\Omega = \frac{\text{area of the cone on surface}}{(\text{sphere radius})^2} = \frac{1}{R^2}\int_0^\theta \underbrace{2\pi \cdot R\sin\theta}_{\text{circonference of the circle r}} \overbrace{R\cdot d\theta}^{\text{Construction of cone form } 0\rightarrow\theta} = 2\pi(1-\cos\theta)$$

$$\text{Small angle approximation: } \Omega = 2\pi(1-\cos\theta) = 4\pi\sin^2\theta/2 \cong 4\pi(\theta/2)^2 \cong \pi\cdot\theta^2$$

In the small angle approximation the solid angle is approximated by the ratio between the surface of the sphere and that of the disk created at the sphere-cone intersection.



Radiometry (Definition 7)

- Radiant intensity: I_e [W/sr]

The radiant intensity is a measure of the intensity of electromagnetic radiation. It is defined as the power per unit solid angle. The SI unit of the radiant intensity is watts per steradiant ($W \cdot sr^{-1}$).

$$I_e = \frac{d\phi_e}{d\Omega}$$

- Radiance: L_e [W/m^2 sr]

The radiance is a radiometric measure describing the amount of light that passes through or is emitted from an area, and propagates within a given solid angle in a specified direction. It is used to characterize both the emission from diffuse sources and reflections from diffuse surfaces

$$L_e = \frac{d^2\phi_e}{dA_{proj}\, d\Omega}$$

L_e is constant along a ray within a homogenous, lossless, isotropic medium!

Radiometry (Note)

- The radiant **intensity** and **radiance** characterize the propagation of a radiation in a specific direction.

For an isotropic point source:

$$E = I/d^2$$

where « d » is the source-detector distance

http://www.rpcphotonics.com/wp-content/uploads/2014/11/Engineered-Diffusers-intensity-vs-irrandiance.pdf

Units derivation

Energy | Power | Intensity

$$
\begin{array}{ccccccccc}
Q & \rightarrow & \dfrac{d}{dt} & \rightarrow & \phi & \rightarrow & \dfrac{d}{d\Omega} & \rightarrow & I \\
\downarrow & & & & \downarrow & & & & \downarrow \\
\dfrac{d}{dA} & & & & \dfrac{d}{dA} & & & & \dfrac{d}{dA} \\
\downarrow & & & & \downarrow & & & & \downarrow \\
H & \rightarrow & \dfrac{d}{dt} & \rightarrow & E & \rightarrow & \dfrac{d}{d\Omega} & \rightarrow & L
\end{array}
$$

Exposure | Irradiance | Radiance

Radiometry (Definitions 8, 9)

Isotropic source and lambertian surface:

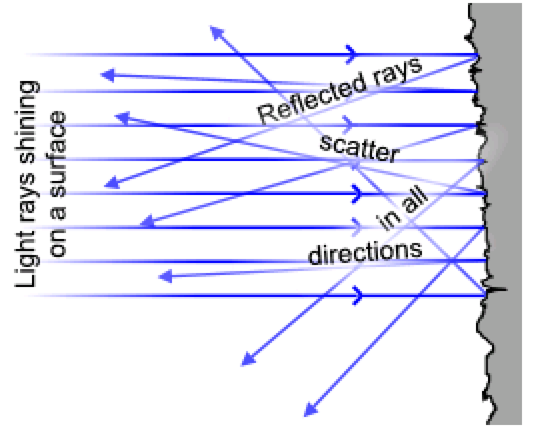
Isotropic surface or source **radiates uniformly in all directions from a spherical source, i.e. the radiant intensity is the same in all directions.**

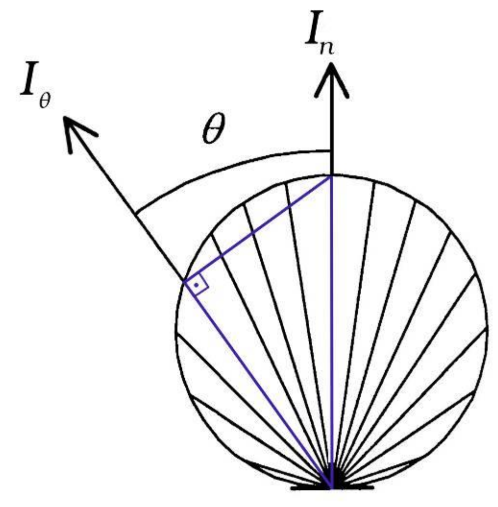
Example: a globular tungsten lamp with a milky white diffuse envelope.

Lambertian surface **is a flat radiating surface (reflecting surface or active surface), which is such that the intensity falls off with the cosine of the observation angle.**

Lambert's emission law or cosine emission law:

$$I_\theta = I_n \cos\theta$$



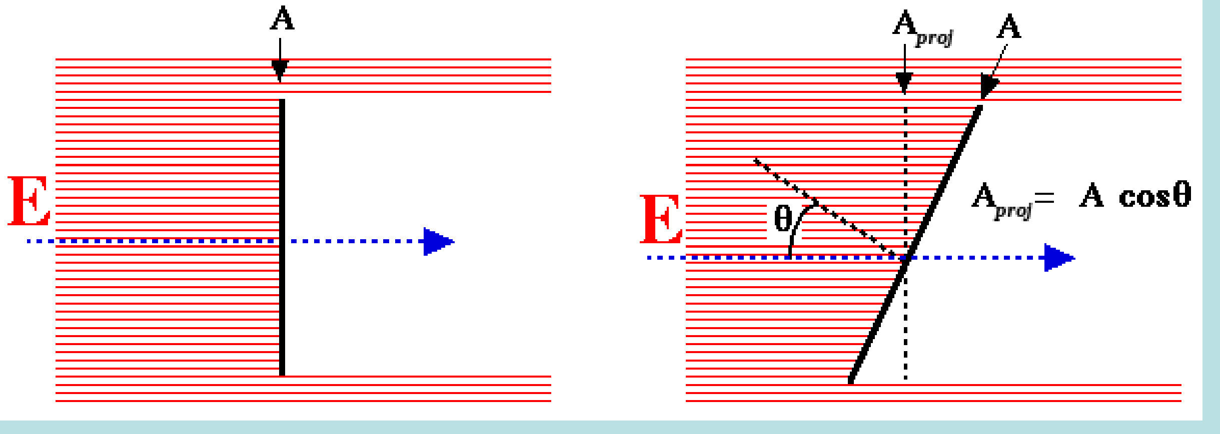


Lambertian reflecting surface

Projected area

- Projected Area: $A_{proj}=A\cos\theta$

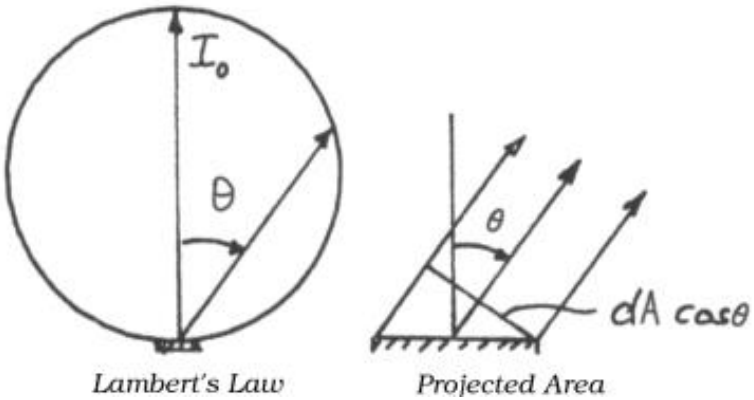
  The projected area is the effective area exposed to the radiation



Radiometry (Note)
Lambertian surfaces

An interesting characteristic of a *Lambertian surface* is that it **has constant radiance independent of the viewing direction**. ($I_\theta = I_0 \cos\theta$)
The luminance being the quantity perceived by our eyes, a (matt) surface with good diffusing properties under uniform illumination is a good example of a Lambertian surface, i.e. the "brightness" will be perceived independently from the angle of view.

- The moon and the sun appear as uniform disk.
- Matt surfaces are very close to be Lambertian surfaces.



$$L = \frac{dI}{dA_{proj}} = \frac{d(I_0 \cos\theta)}{d(A\cos\theta)} = \frac{dI_0}{dA} = \text{const.}$$

In this case, the emittance is related to the radiance (or luminance) by:

$$M = \pi \cdot L$$

Demonstration of π factor

Emittance for a lambertian surfaces :

$$M = \int_0^{2\pi} \frac{I_0 \cos\theta}{A} d\Omega = \int L \cos\theta \, d\Omega = L \int \cos\theta \, d\Omega$$

Solid angle Ω defined by a cone of half apperture angle θ

$$\Omega = 2\pi(1-\cos\theta) \rightarrow \theta_{(\Omega=0)} = 0, \theta_{(\Omega=2\pi)} = \pi/2$$

$$d\Omega = 2\pi \sin\theta \, d\theta$$

$$M = 2\pi \, L \int_0^{\pi/2} \sin\theta \cos\theta d\theta = 2\pi \, L \underbrace{\left(-\frac{1}{2}\cos^2\theta \Big|_0^{\pi/2} \right)}_{1/2}$$

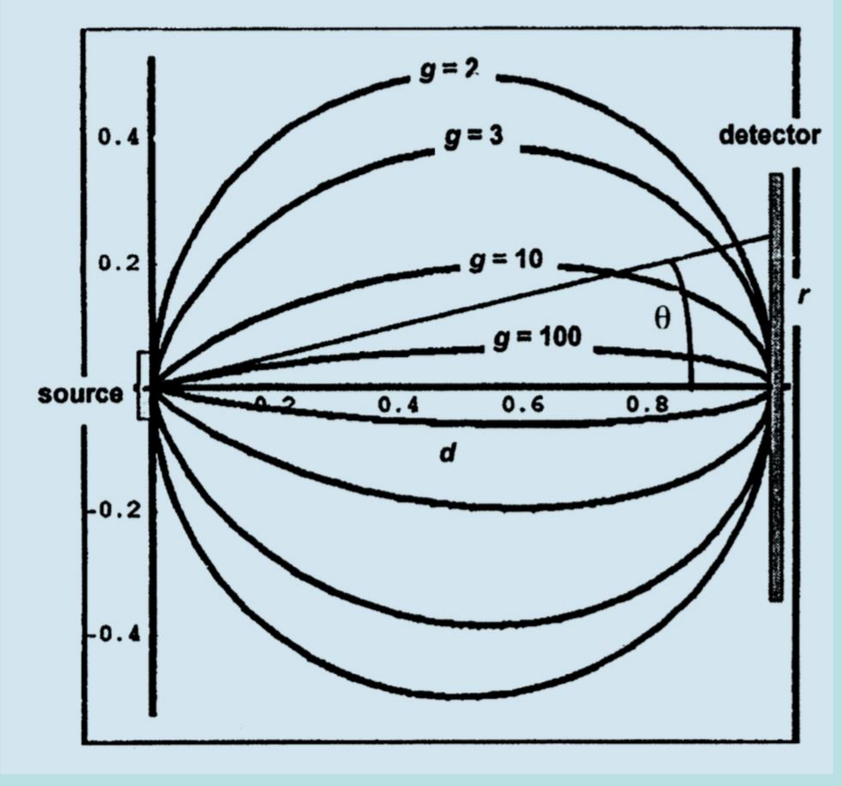
$$M = \pi L$$

Angular distribution patterns of sources with rotational symmetry

$$I=I_0\cos^{g-1}\theta$$

Where I_0 is the intensity normal to the source itself and $g\geq 1$.

For example:



g = 1 for an isotropic point source

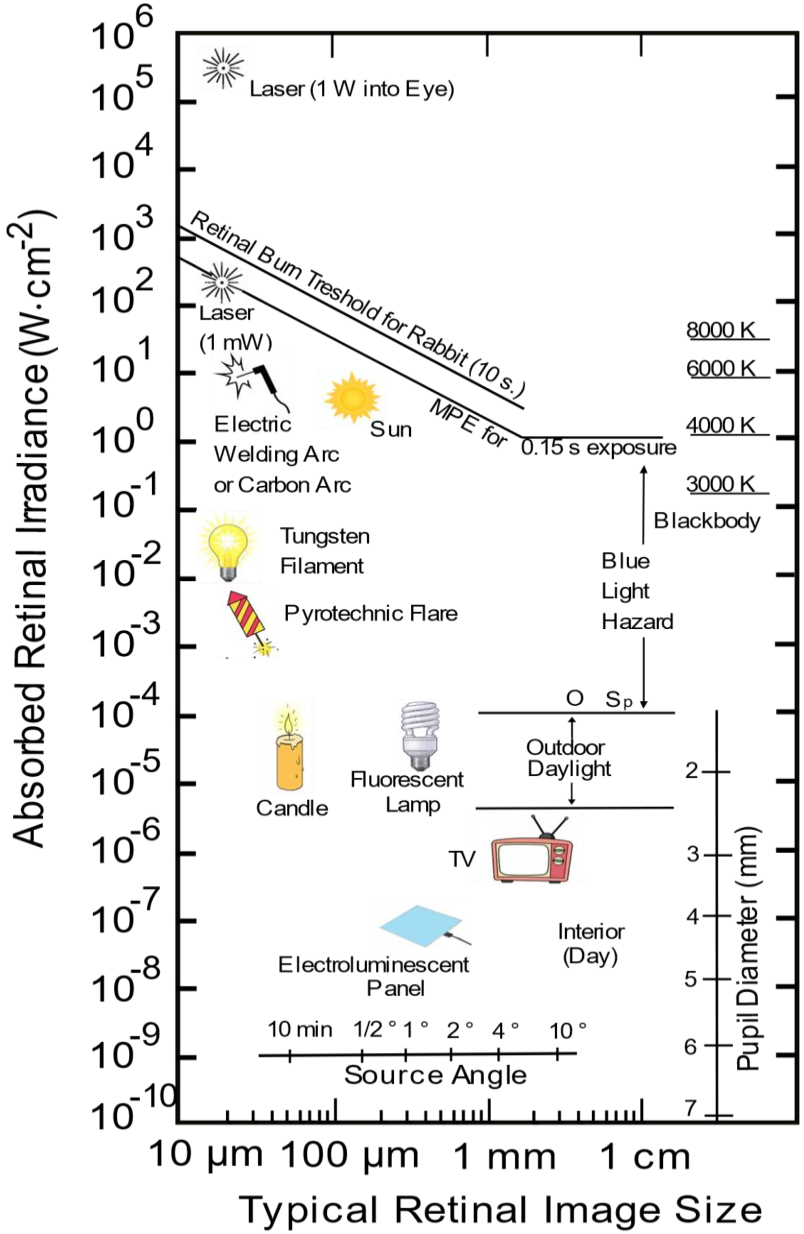
g = 2 for a Lambertian point source

g > 30 for an LED point source (LED lamp)

Photometry

Absorbed retinal irradiance

The eye is exposed to light sources having radiances varying from approximately 10^4 [W cm^{-2} sr^{-1}] to approximately 10^{-6} [W cm^{-2} sr^{-1}].

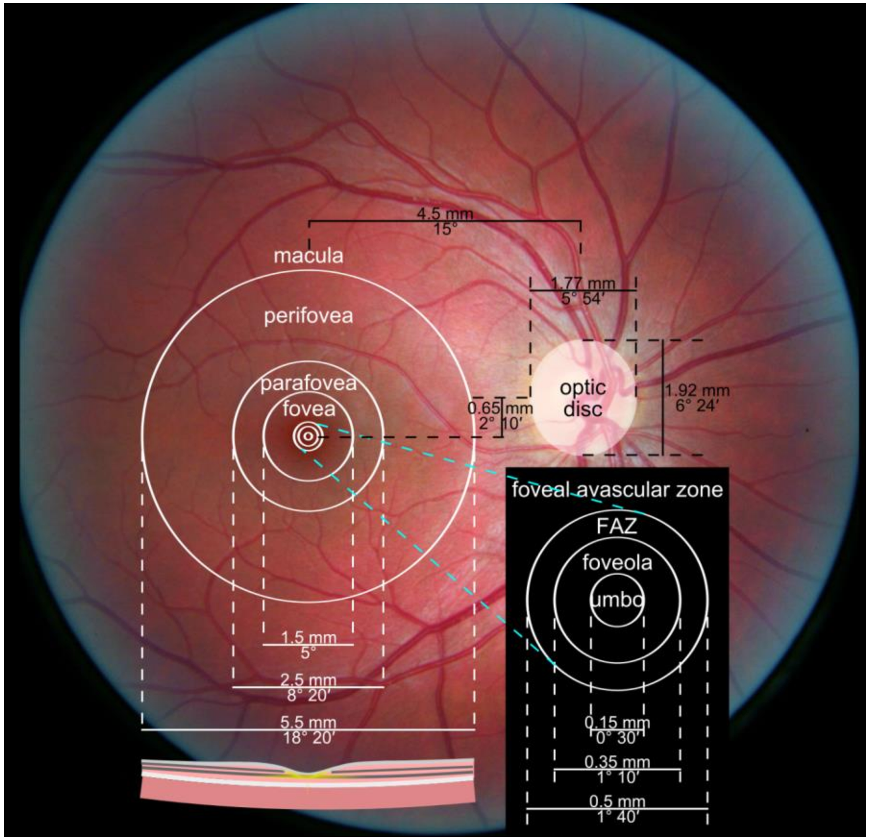


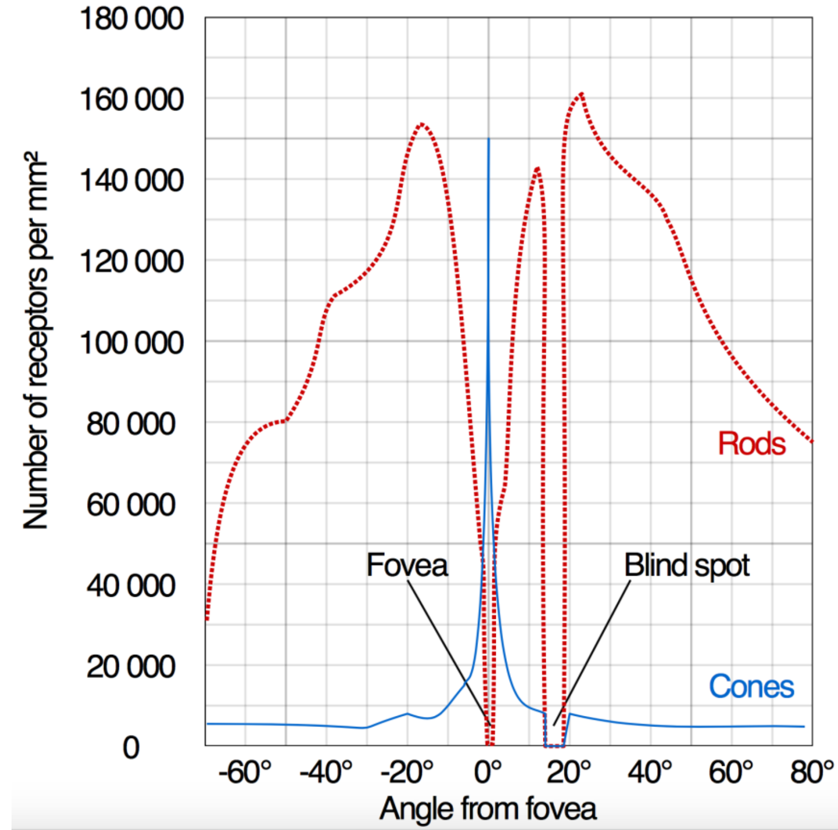
Photometry

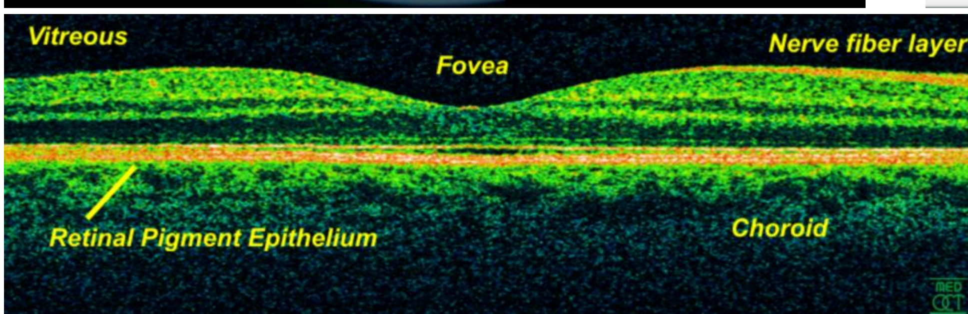
- Photometry is a quantitative science based on a statistical model of the human visual response under photopic condition, i.e. our perception of light under carefully controlled daylight illumination condition.
- Radiometric terms have to be weighted with the human eye's spectral response to find the corresponding photometric value.
  - **Candela [cd] is the base unit in photometry**. It describes the amount of luminous intensity (radiant intensity in radiometry) emitted by a monochromatic source (555 nm, 540 THz) which radiant intensity is 1/683 W/sr.
  - Lumen [lm] is the luminous flux (radiant flux or power) emitted by a source.

Photometry unit definition		
Lumen	lm	$cd \cdot sr$
Lux	lx	$cd \cdot sr \cdot m^{-2}$

Location of the macula







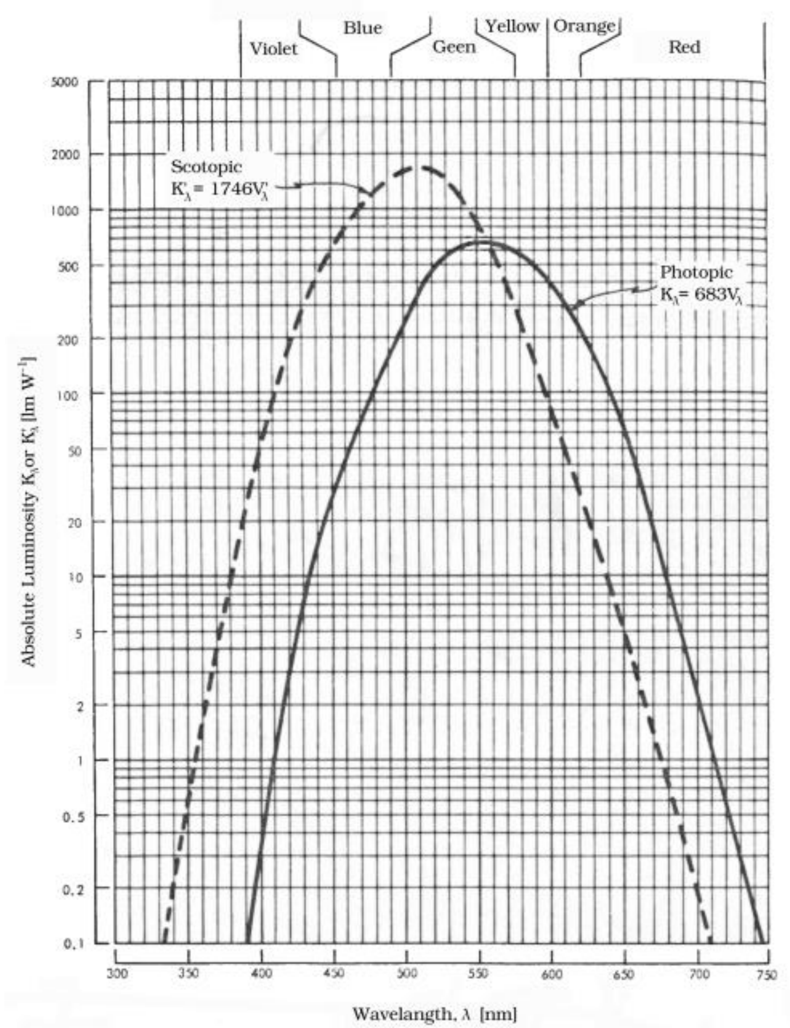
OCT cross-section image at 800 nm

Photometry

There is two types of retinal receptors in the eye, rods and cones. The eye's spectral responsivity in dark-adapted (scotopic) state is considerably different from that in light-adapted (photopic) state.

Photopic Eye Response is the response of the cones in the retina and it occurs after the eye have become adapted to a field of luminance equal or greater than about 3 cd/m^2. The peak luminosity of 683 lm/W for photopic vision occurs at a wavelength of about 555 nm

Scotopic Eye Response is the response of the rods in the retina and it occurs after the eye have become adapted to a field of luminance equal or less than about 3 x10-5 cd/m2. To become dark-adapted the eye take up to 30 min. The peak luminosity of 1746 lm/W for scotopic vision occurs at a wavelength of about 510 nm.



Conversion between Radiometric and Photometric terms

Numerical values of the normalized photopic curve V(λ)

Wavelength [nm] → | 380 | 40 x10^{-6} |

Photopic Luminous Efficiency V(λ) ↗

To convert a radiometric quantity R_Q [W] to the corresponding photometric quantity P_Q [lm] one needs only to integrate the product of the radiation spectral distribution with the normalized photopic curve (V(λ)) and multiply the results by the conversion factor k = 683 lm/W

$$P_Q = k \int_{\lambda_1}^{\lambda_2} R_Q \, V(\lambda) \, d\lambda$$

$$P_Q \approx k \sum R_{Q,n} \, V_n(\lambda) \, \Delta\lambda$$

380	40x10^{-6}	520	710x10-3	650	107x10^{-3}
390	120x10^{-6}	530	862x10^{-3}	660	61x10^{-3}
400	400x10^{-6}	540	954x10^{-3}	670	32x10^{-3}
410	1.2x10^{-3}	550	995x10^{-3}	680	17x10^{-3}
420	4x10^{-3}	555	1	690	8.2x10^{-3}
430	11.6x10^{-3}	560	995x10^{-3}	700	4.1x10^{-3}
440	23x10^{-3}	570	992x10^{-3}	710	2.1x10^{-3}
450	38x10^{-3}	580	870x10^{-3}	720	105x10^{-6}
460	60x10^{-3}	590	757x10^{-3}	730	52x10^{-6}
470	91x10^{-3}	600	631x10^{-3}	740	25x10^{-6}
480	139x10^{-3}	610	503x10^{-3}	750	12x10^{-6}
490	208x10^{-3}	620	381x10^{-3}	760	6x10^{-6}
500	323x10^{-3}	630	265x10^{-3}	770	3x10^{-6}
510	503x10^{-3}	640	175x10^{-3}	780	1x10^{-6}

Photometry (Definition 1)

- Luminous Energy: Q_v[lm s] = 683 Q_e [J] V(λ)
  Luminous energy is the perceived energy of light. This is sometimes also called the quantity of light.

- Luminous Exposure: H_v [lx s] = 683 H_e [Jm^{-2}] V(λ)
  Luminous exposure is the perceived exposure.

- Luminous Flux or Power: ϕ_v [lm] = 683 ϕ_e [W] V(λ)
  Luminous flux is the perceived emission power of the source. It's often used to characterize the light sources, but pay attention to the solid angle specification.

- Luminous Flux Density [Lux] (M_v: Emittance; E_v: Illuminance): E_v, M_v [lm/m^2] = 683 M_e, E_e [Wm^{-2}] V(λ)

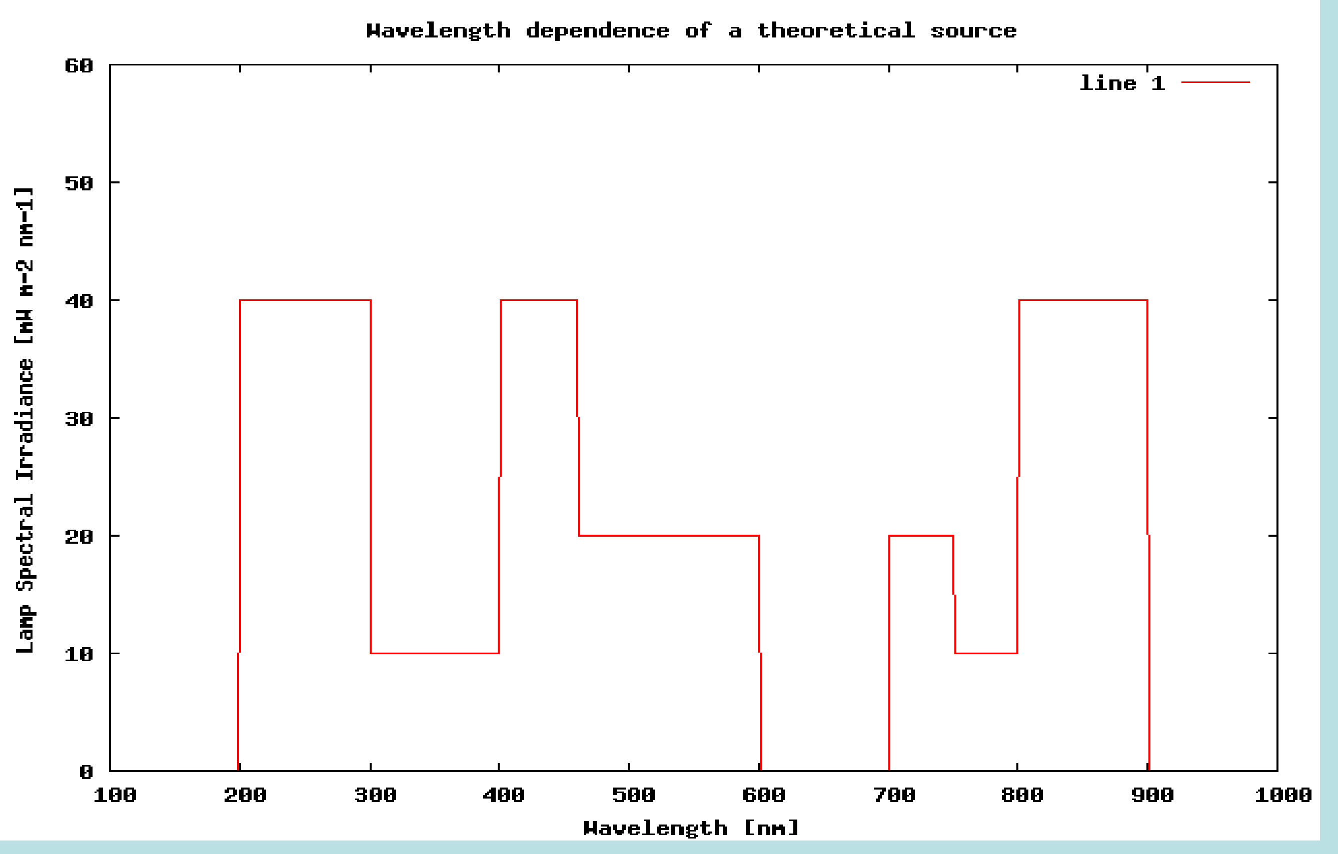
Photometry (Definition 2)

- Luminous Intensity: I_v [cd] = 683 I_e [W/sr] $V(\lambda)$
  Luminous intensity is the luminous flux (radiant flux or power), emitted in a specific solid angle.

- Luminance [cd/m^2]: L_v [cd/m^2] = 683 [W/sr.m^2] L_e $V(\lambda)$
  This is the photometrically weighted radiance (L_e).
  This term describe the quantity perceived by the eye. It describes how «bright» a surface appears in a given direction.

Example: Source model

Find the illuminance generated by a lamp producing the following spectral irradiance :



Example (cont.)

1. Lamp illuminance:

Wavelength Range [nm]	Lamp spectral Irradiance [mW m^{-2} nm^{-1}]	V(λ)	Δλ	$E_e \cdot V(\lambda) \cdot \Delta\lambda$
200 – 300	40	0	100	0
300 – 380	10	0	80	0
380 – 400	10	≈1.86E-4	20	0.0372
400 – 460	40	≈1.97E-2	60	47.4
460 – 600	20	≈0.631	140	1766.8
600 – 700	0	≈0.2	100	0
700 – 750	20	≈1.07E-3	50	1.06
750 – 780	10	≈5.5E-6	30	0.002
780 – 800	10	0	20	0
800 – 900	40	0	100	0
			Total	**≈1815**

$$E_v = 683\, {}^{lm}\!/_{W} \left(\sum_n \left(E_{e,n} V(\lambda_n)\right) \cdot \Delta\lambda \right) = 1240\,\text{lux (or } {}^{\text{lm}}\!/_{\text{m}^2}\text{)}$$

Example: Video Pojector

As an example, a small video projector is considered (Toshiba TDP FF1):

Illuminance [E_v] = 400 lux
Image aspect ratio = 16:9
Diagonal = 173 cm

Luminous Flux [ϕ_v] = 480 lm
Luminance [L_v] = 1740 cd m^{-2}

Example: Outdoor light

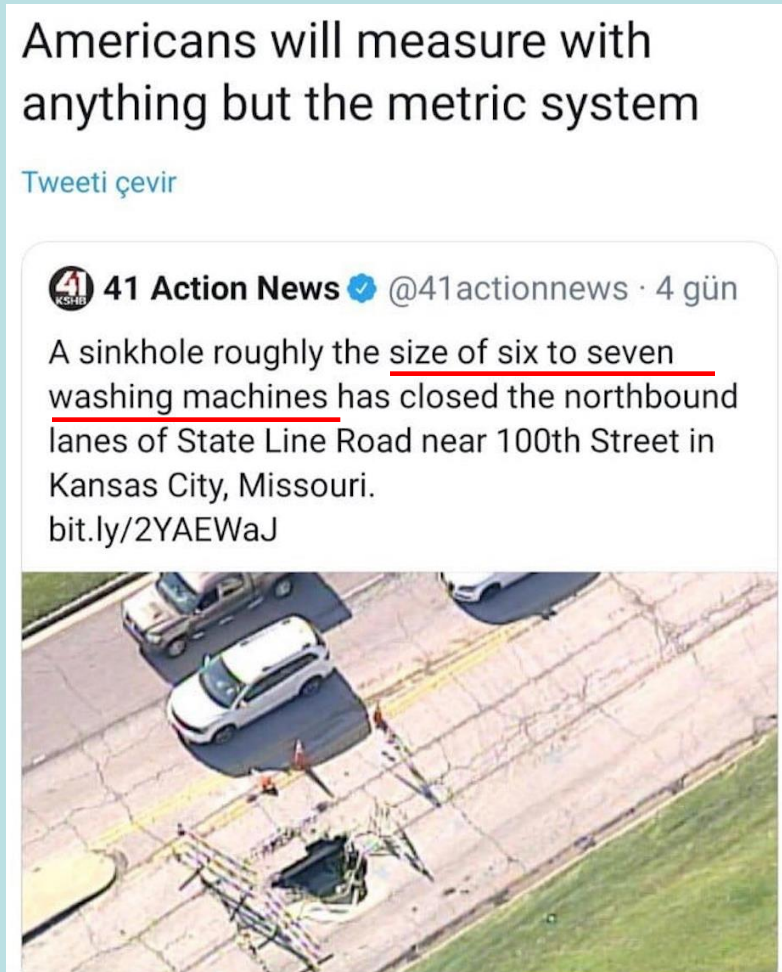
Condition	Illumination LUX
Full Daylight	10,752
Overcast Day	1,075
Very Dark Day	107
Twilight	10.8
Deep Twilight	1.08
Full Moon	0.108
Quarter Moon	0.0108
Starlight	0.0011

Source: http://sustainabilityworkshop.autodesk.com/buildings/measuring-light-levels

Units names

Symbol	English	French	German	Units
Q_e	Radiant energy	Energie radiante	Strahlungenergie	J
ϕ_e, P_e	Radiant Flux, or Radiant power	Flux énergétique	Strahlungsfluss	W
E_e	Irradiance	Éclairement énergétique	Bestrahlungsstärke	W/m^2
H_e	Radiant Exposure	Exposition énergétique	Bestrahlung	J/m^2
L_e	Radiance	Luminance énergétique	Strahlstärke	$W\ sr^{-1}\ m^{-2}$
I_e	Radiant Intensity	Intensité énergétique	Strahlstärke	$W\ sr^{-1}$
Q_v	Quantity of light	Quantité de lumière	Lichtmenge	lm s
ϕ_v, P_v	Luminous Flux	Flux lumineux	Lichtstrom	lm
E_v	Illuminance	Éclairement lumineux ou émittance	Beleuchtungsstärke	$lx = lm/m^2$
H_v	Light Exposure $H = E\,t$	Exposition lumineuse ou lumination	Belichtung	lx s
L_v	Luminance	Luminance	Leuchtdichte	cd/m^2 [$lx\ sr^{-1}$]
I_v	Luminous intensity	Intensité lumineuse	Lichtstärke	cd [$cd = lm/sr = lx\ m^2\ sr^{-1}$]

Conversion Factors



Luminance Conversion Factors

Multiply Luminance in → To Obtain Luminance in ↓ By ↘	Footlambert	Nit	Millilambert	Candela/in^2
Footlambert (ftL)	1	0.2919	0.929	452
Nit (cd/m^2)	3.426	1	3.183	1,550
Millilambert (mL)	1.076	0.3142	1	487
Candela/in^2	0.00221	0.000645	0.00205	1
Candela/ft^2	0.3183	0.0929	0.2957	144
Stilb (cd/cm^2)	0.00034	0.0001	0.00032	0.155
Lambert	0.000108	0.000314	0.001	0.487

Multiply Luminance in → To Obtain Luminance in ↓ By ↘	Candela/ft^2	Stilb	Lambert	Apostilb (Blondel)
Footlambert (ftL)	3.142	2,919	929	0.0929
Nit (cd/m^2)	10.76	10,000	3,183	0.318
Millilambert (mL)	3.382	3,142	1,000	0.1
Candela/in^2	0.00694	6.45	2.05	0.0002
Candela/ft^2	1	929	295.7	0.0296
Stilb (cd/cm^2)	0.00108	1	0.318	0.000032
Lambert	0.00338	3.442	1	0.0001

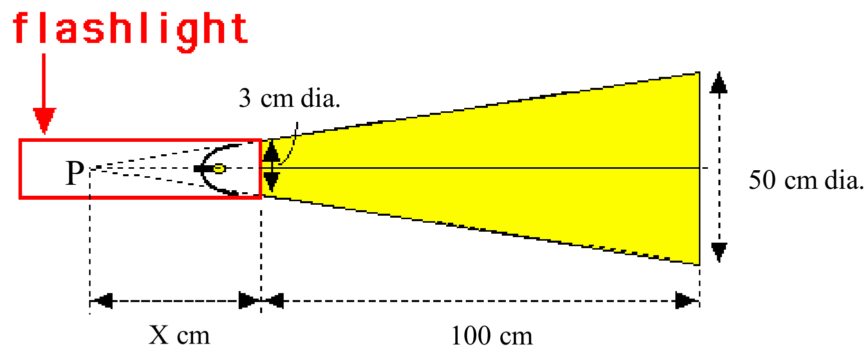
Illuminance Conversion Factors

Multiply Number of → To Obtain Number of ↓ By ↘	Footcandles (ftcd)	Lux (lx)	Phot (lm/cm^2)	Milliphot (mlm/cm^2)
Footcandles (ftcd)	1	0.0929	929	0.929
Lux (lx)	10.76	1	10,000	10
Phot (lm/cm^2)	0.00108	0.0001	1	0.001
Milliphot (mlm/cm^2)	1.076	0.1	1,000	1

References

- Biomedical Optics, Oregon Graduate Institute (http://omlc.ogi.edu)
- Optical Sciences Center, University of Tucson (http://www.optics.arizona.edu/Palmer/rpfaq/rpfaq.htm)
- Ian Ashdown (http://www.helios32.com/Measuring%20light.pdf)
- Newport, technical information (http://www.newport.com/Technical-Information/381840/1033/catalog.aspx)
- RCA Electro-optic Devices handbook, ISBN: 09 1397 011 5, pages 5.1-5.12
- Laser in Ophthalmology, ISBN: 90 6299 189 0, page 2-5
- The science of phototherapy: An introduction, ISBN: 14 0202 883 0, pages 30-50

Exercise for week 2: 15.09.2025



A flashlight project a light beam of 50 mW to create a homogenous spot on a wall 100 cm away.

1. Find the solid angle of the cone of light radiating from the flashlight
2. Find the radiant intensity of the beam
3. Find the irradiance and illuminance of the spot (the lamp has a constant spectral radiance and emits light between 400 and 800 nm only)
4. Find the radiance and luminance of the lamp, in a direction corresponding to its optical axis
   Note: The flashlight looks like a uniform disk as seen from the wall!
5. Find the irradiance and radiance of the lamp if the wall is placed at 2.(x+100) cm instead of (x+100) cm from the point "P". Why is it so that the radiance is not exactly the same as compare to the value you obtained in question 4?

Exercise: Hint

1. Lamp illuminance:

Wavelength Range [nm]	Lamp spectral Irradiance [mW m^{-2} nm^{-1}]	V(λ)	Δλ	$E_e \cdot V(\lambda) \cdot \Delta\lambda$
200 – 300	40	0	100	0
300 – 380	10	0	80	0
380 – 400	10	≈1.86E-4	20	0.0372
400 – 460	40	≈1.97E-2	60	47.4
460 – 600	20	≈0.631	140	1766.8
600 – 700	0	≈0.2	100	0
700 – 750	20	≈1.07E-3	50	1.06
750 – 780	10	≈5.5E-6	30	0.002
780 – 800	10	0	20	0
800 – 900	40	0	100	0
			Total	**≈1815**

$$E_v = 683\, {}^{lm}/_{W} \left(\sum_n \left(E_{e,n} V(\lambda_n) \right) \cdot \Delta\lambda \right) = 1240 \text{ lux (or } {}^{\text{lm}}/_{\text{m}^2})$$

Exercise 1
(In class)

What is the parameter you must consider when you want to buy a "lamp" in order to have a better vision when this lamp will be installed in your living room (note: do not consider the directional aspect of the lamp emission)?

- ☐ The power consumed by the lamp expressed in watts.
- ☐ The power emitted by the lamp expressed in watts.
- ☐ The efficiency of the lamp expressed in %.
- ☐ The luminous flux of the lamp expressed in lumen.
- ☐ The luminous intensity of the lamp expressed in candela.
- ☐ The radiance of the lamp expressed in watts/sr^{-1} m^{-2}

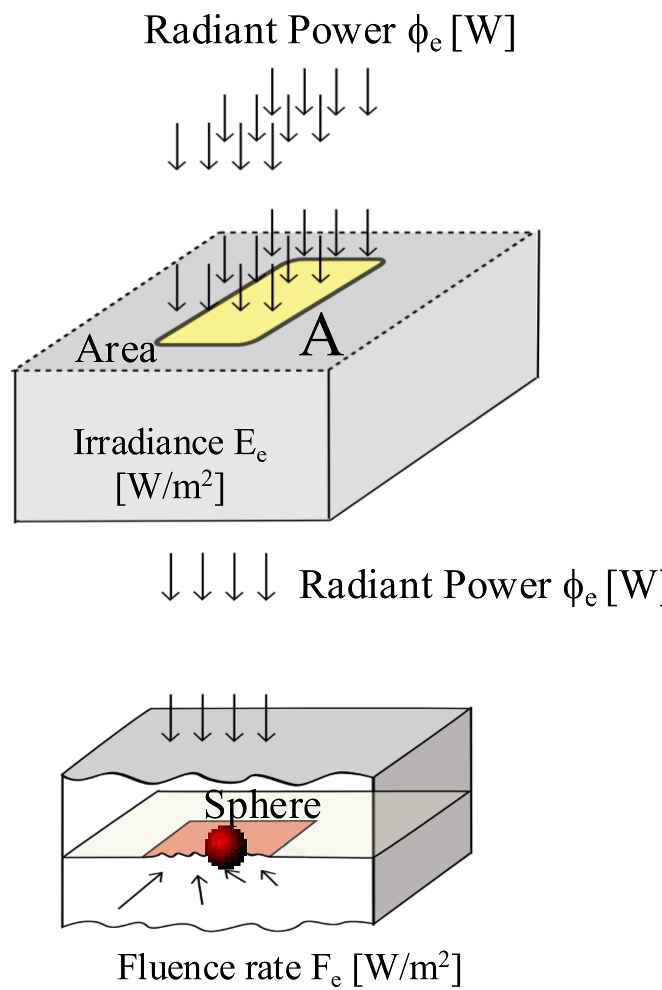
Exercise 2
(In class)

Difference between
Fluence rate and Irradiance !

Radiometry (Definitions)

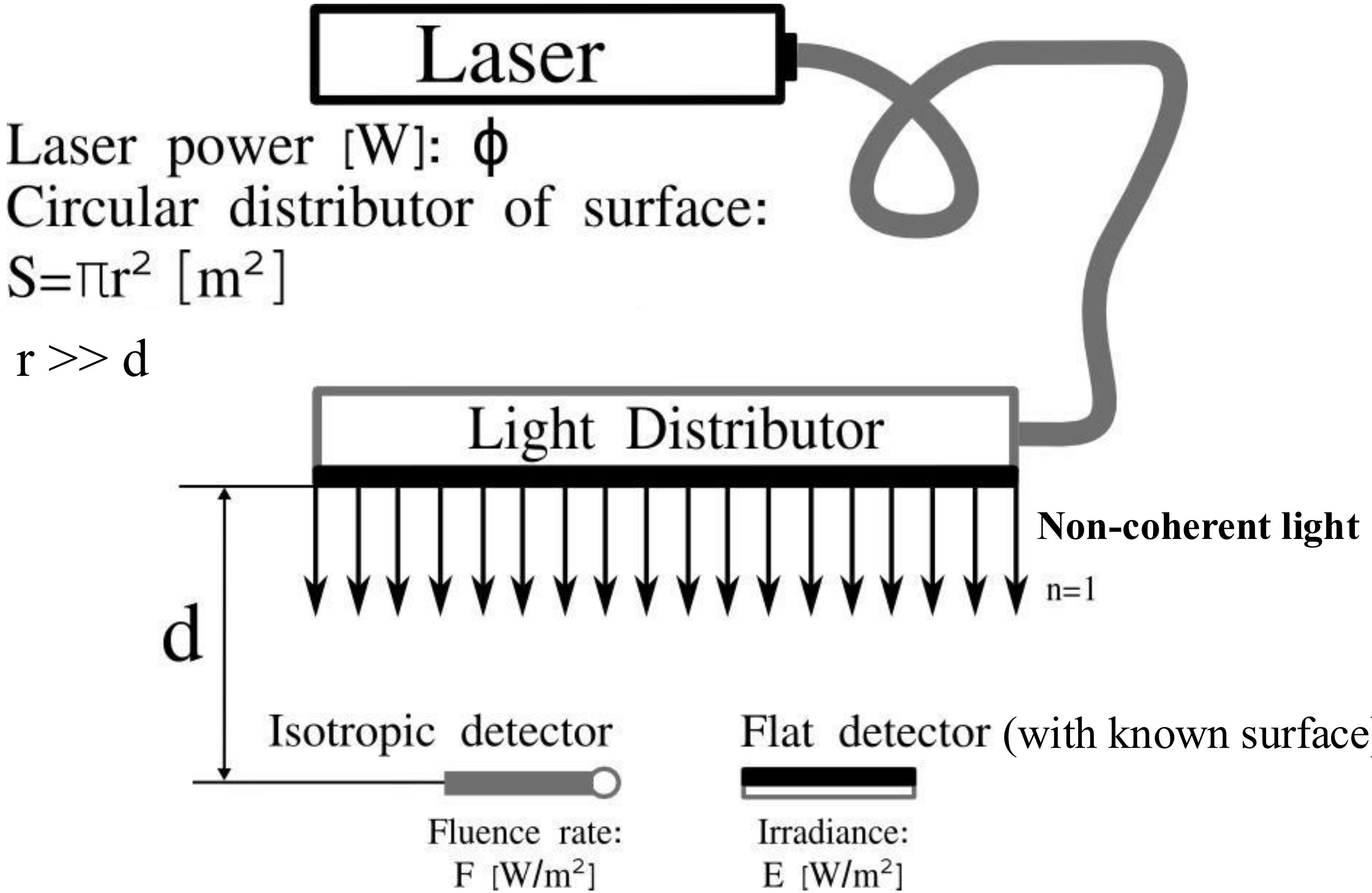
Irradiance vs. Fluence rate

- The irradiance is the radiant flux per unit area reaching the surface A.
- The fluence rate is the quantity measured with an isotropic power meter.
  (Power entering a sphere presenting a unit cross-section)



Exercise 2

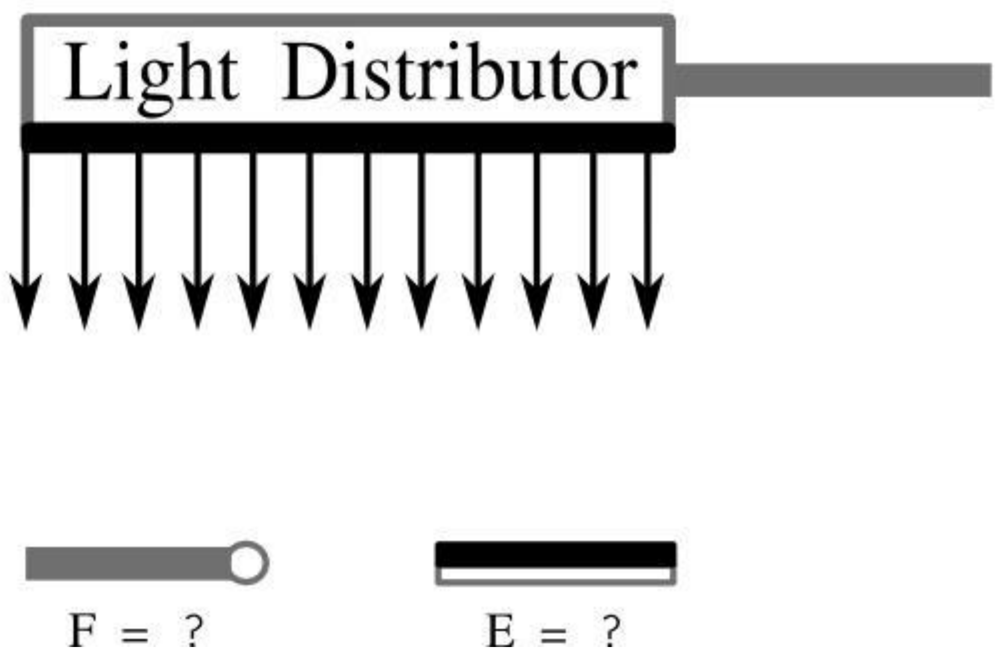
Fluence rate and Irradiance



Case 1

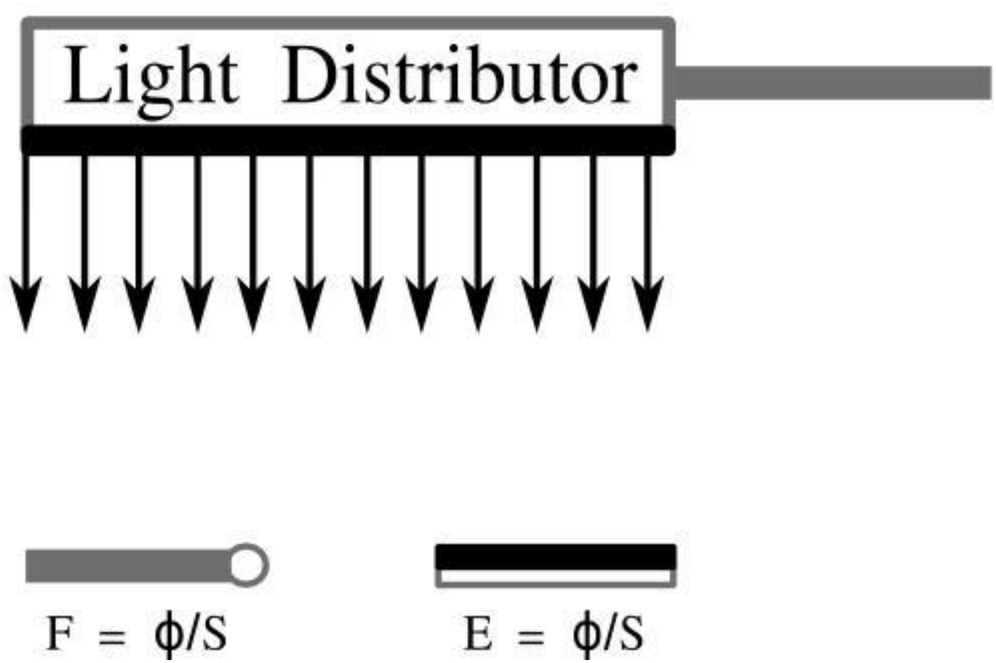
Laser power [W]: ϕ

Distributor surface [m^2]: S



Case 1 (solution)

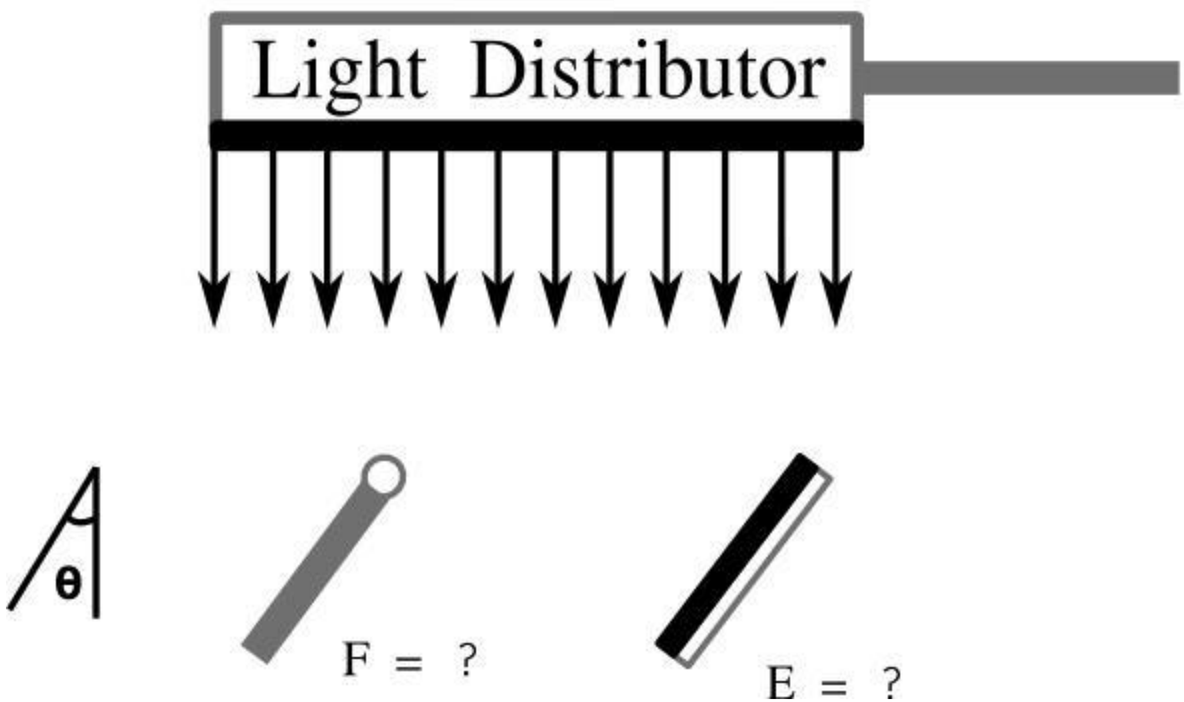
Laser power [W]: ϕ
Distributor surface [m^2]: S



Case 2

Laser power [W]: ϕ

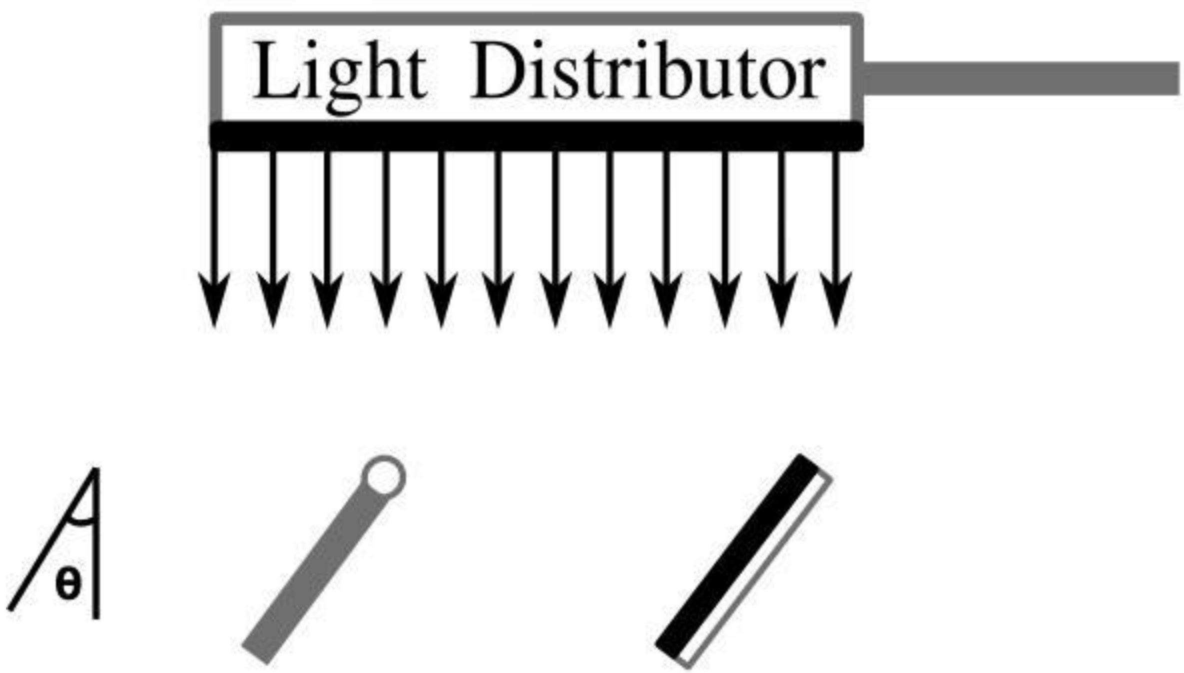
Distributor surface [m^2]: S



Case 2 (solution)

Laser power [W]: ϕ

Distributor surface [m^2]: S

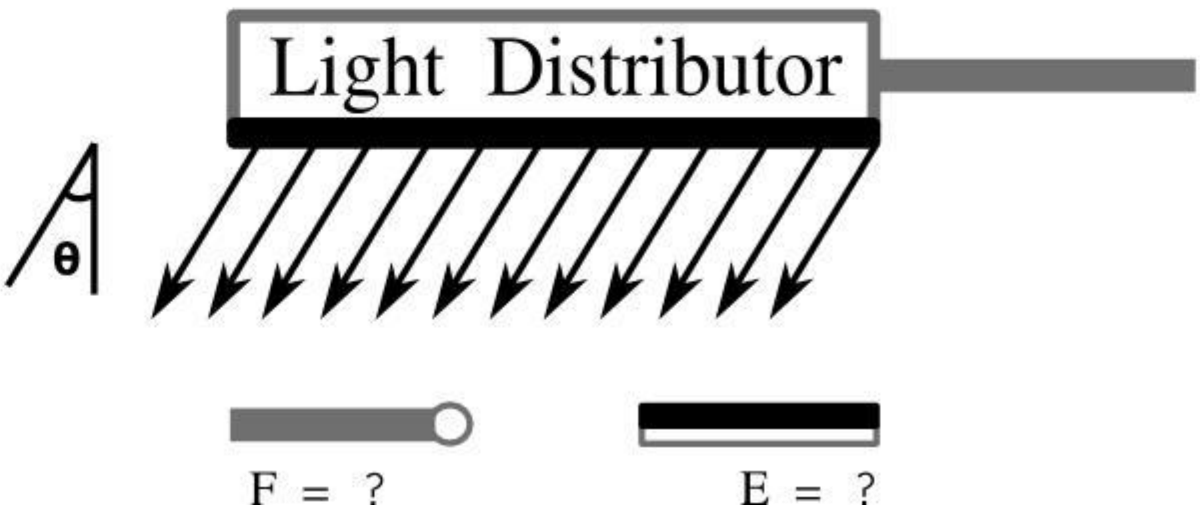


$F = \phi/S$

$E = (\phi/S)\sin\theta$

Case 3

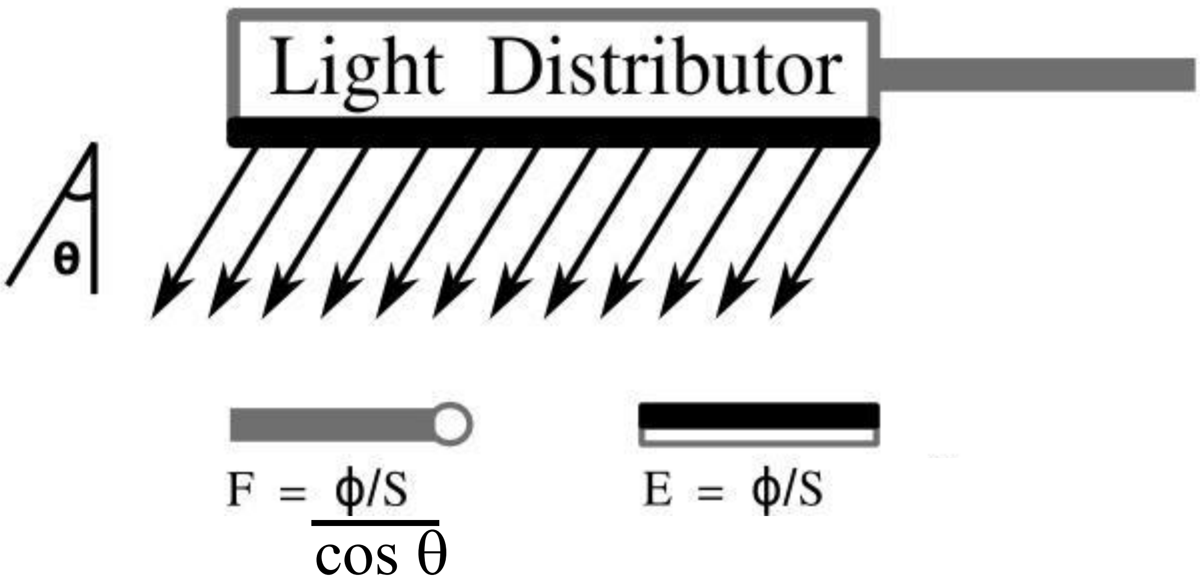
Laser power [W]: ϕ
Distributor surface [m^2]: S



Case 3 (solution)

Laser power [W]: ϕ

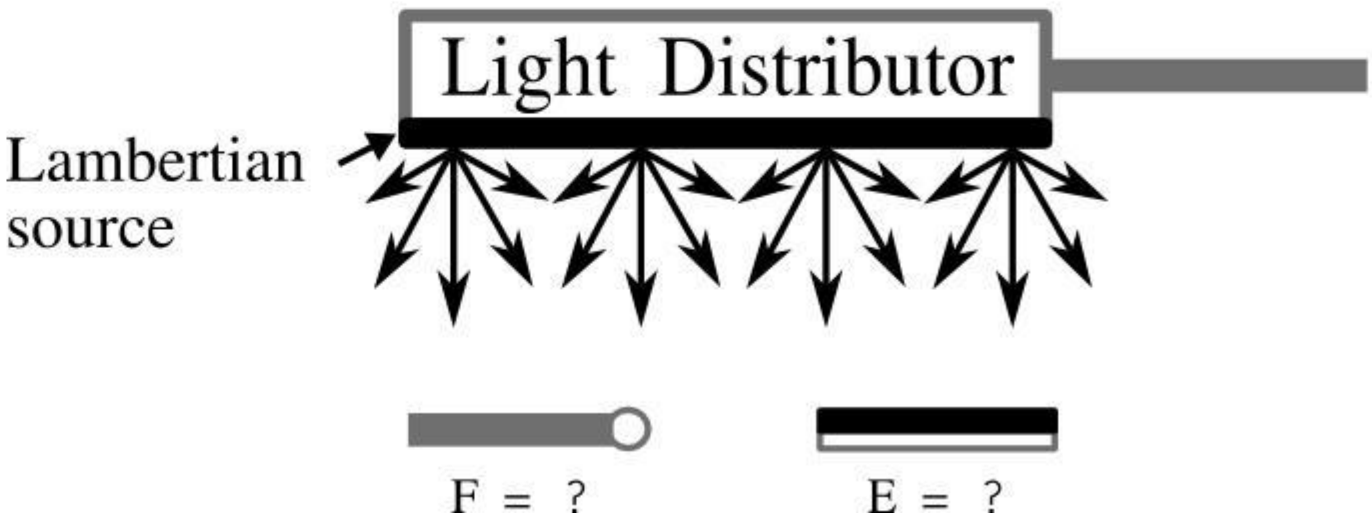
Distributor surface [m^2]: S



Case 4

Laser power [W]: ϕ

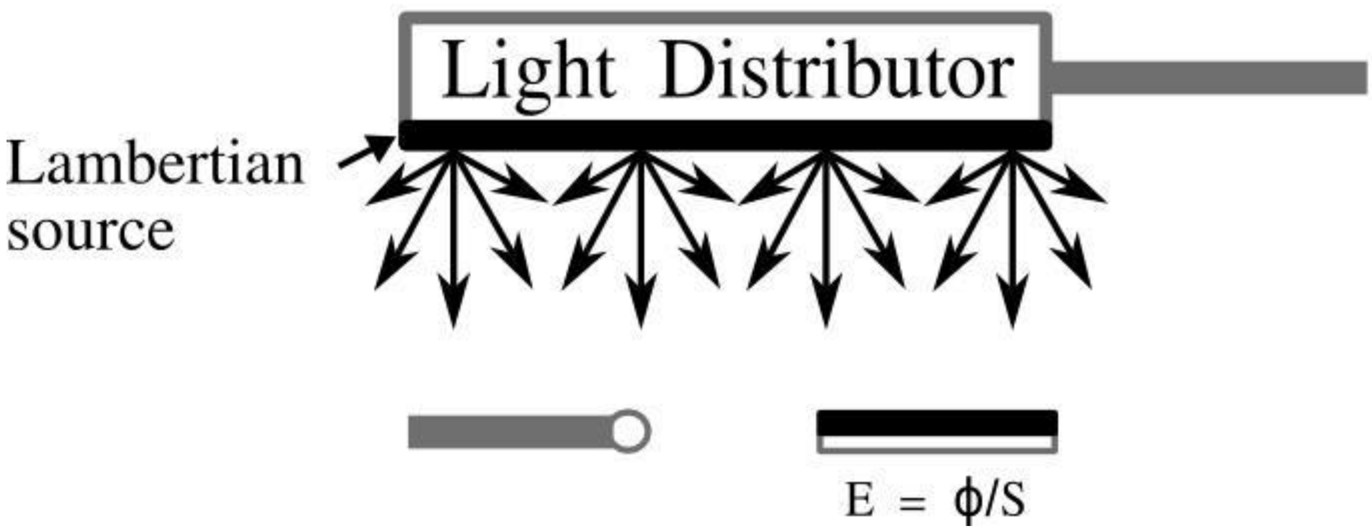
Distributor surface [m^2]: S



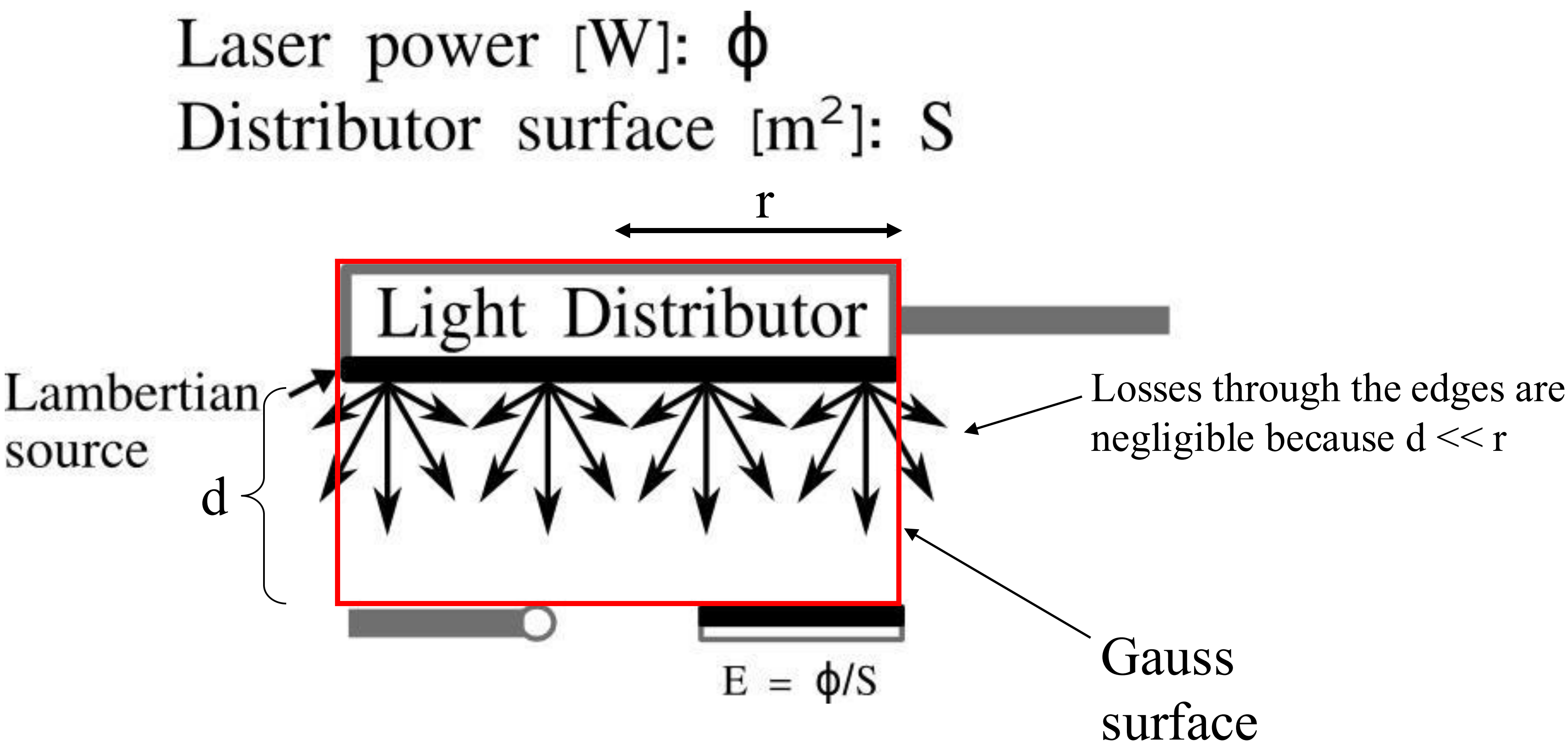
Case 4 (solution)

Laser power [W]: ϕ

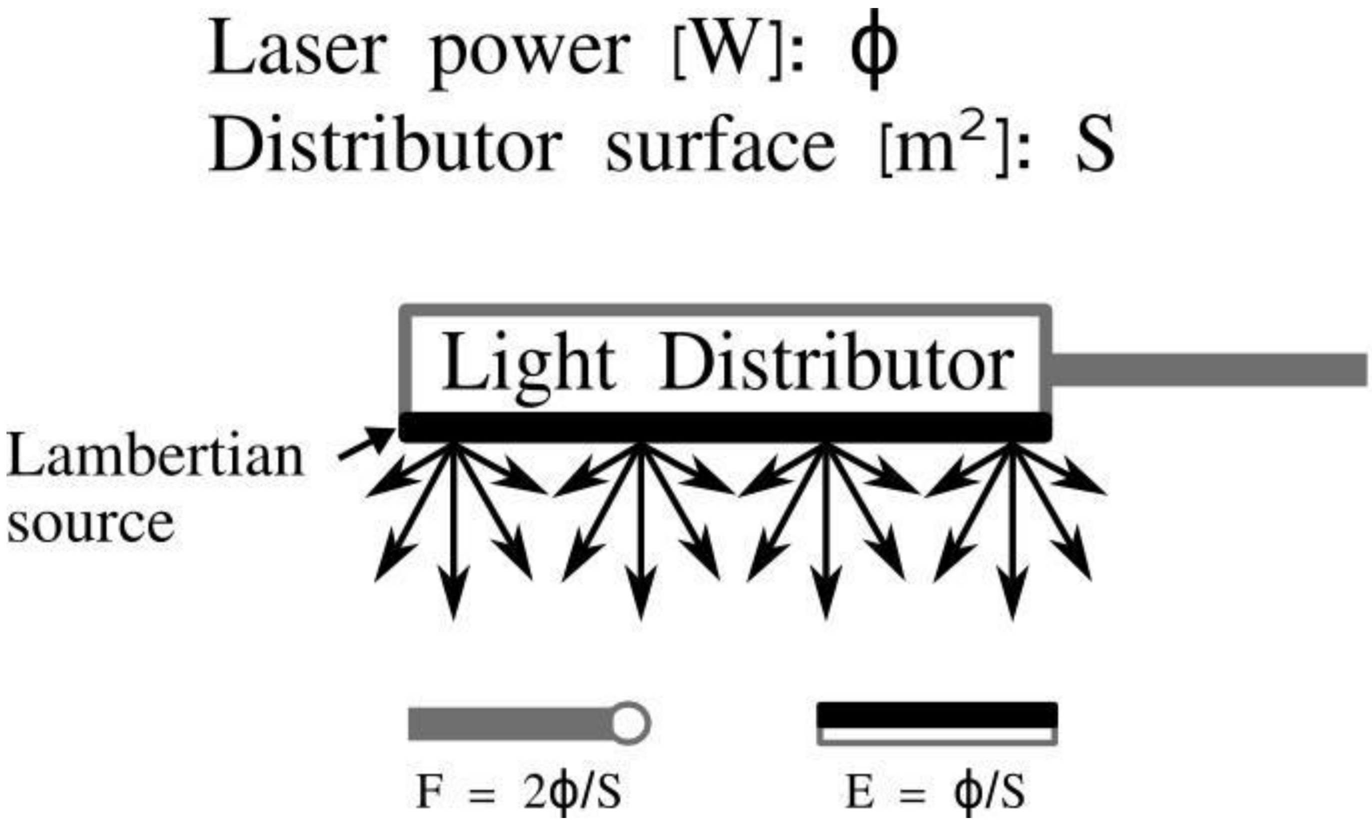
Distributor surface [m^2]: S



Case 4 (solution)



Case 4 (solution)



Case 4

Definitions

S = source surface

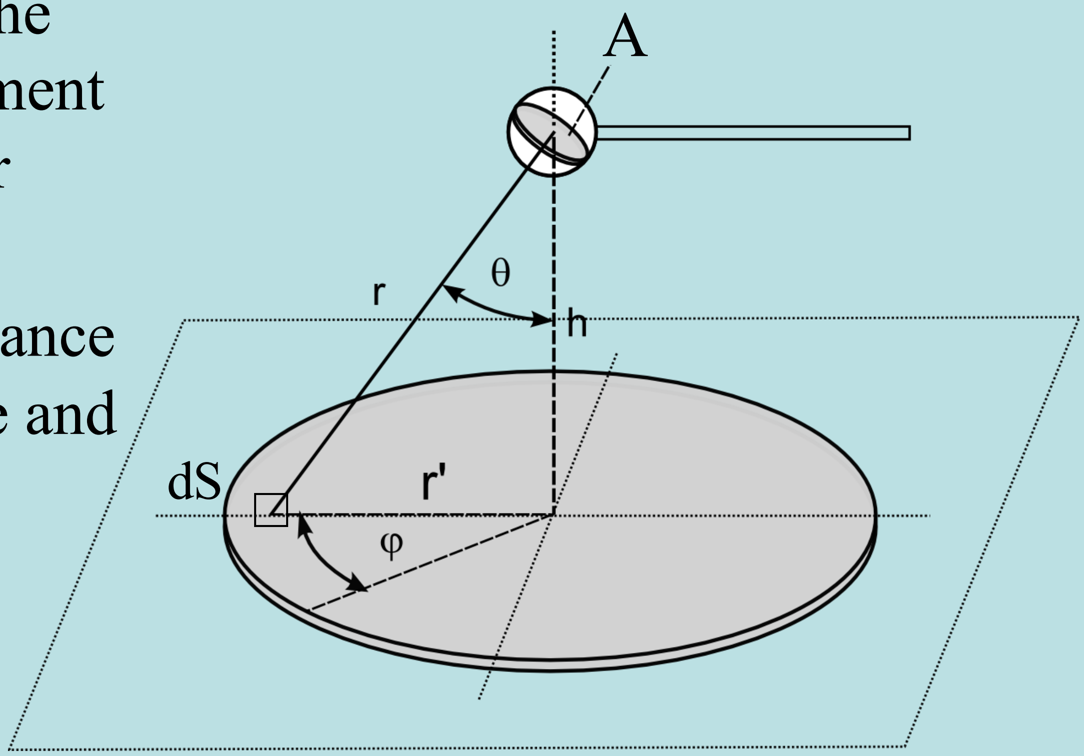
A = detector surface (i.e. the cross section of the isotropic probe)

r = distance between the source surface element dS and the detector surface A

h = the orthogonal distance between the source and the detector

$r = h/\cos\theta$

$r' = h\tan\theta$



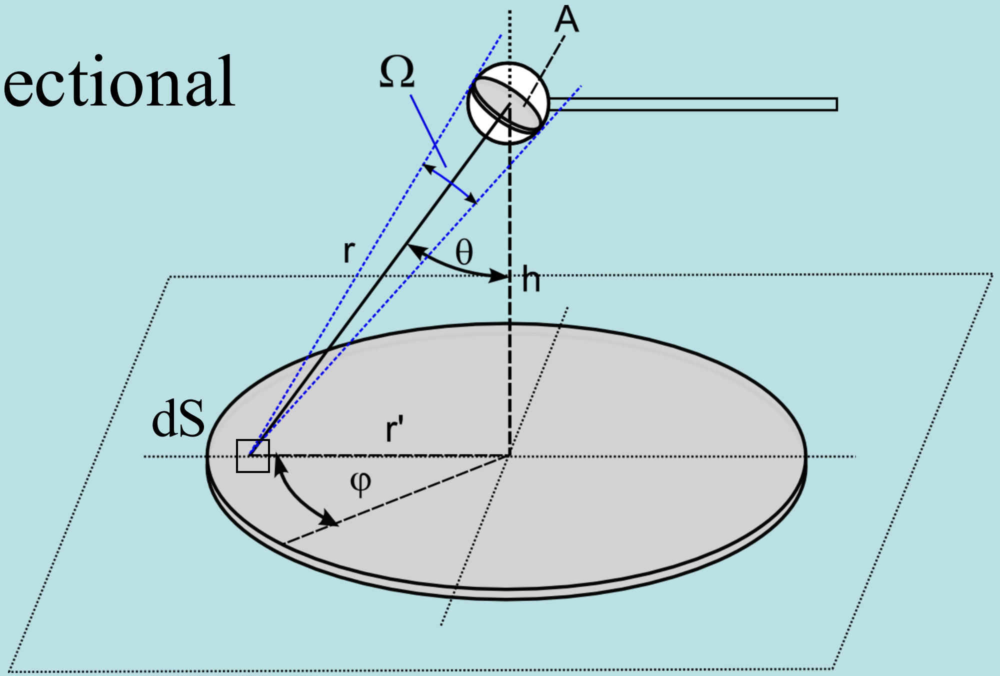
Case 4

Fluence Rate (definition)

Definition:

The radiant fluence rate F at a given point in space is defined as the radiant flux Φ incident on a small sphere, divided by the cross-sectional area A of that sphere

$$F = \frac{\Phi'}{A}$$



with

$$\Phi' = \int L \cdot dS \cdot \cos\theta \cdot \Omega$$

$$F = \frac{1}{A} \int_S L \cdot dS \cos\theta \; \Omega$$

$$= \frac{1}{A} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L \frac{h^2}{\cos^2\theta} \tan\theta \; d\theta \; d\varphi \cdot \cos\theta \cdot A \frac{\cos^2\theta}{h^2}$$

$$= \int_0^{2\pi} \int_0^{\frac{\pi}{2}} L \cdot \tan\theta \cdot \cos\theta \; d\theta \; d\varphi$$

$$= 2\pi \int_0^{\frac{\pi}{2}} L \cdot \cos\theta \cdot \tan\theta \; d\theta$$

$$= 2\pi \cdot L = 2M = 2\frac{\Phi}{S}$$

Definition of the solid angle

$$\Omega = \frac{A}{r^2} = A \cdot \frac{\cos^2\theta}{h^2}$$

From the set-up geometry

$$dS = r' dr' d\varphi$$

$$r' = h \cdot \tan\theta$$

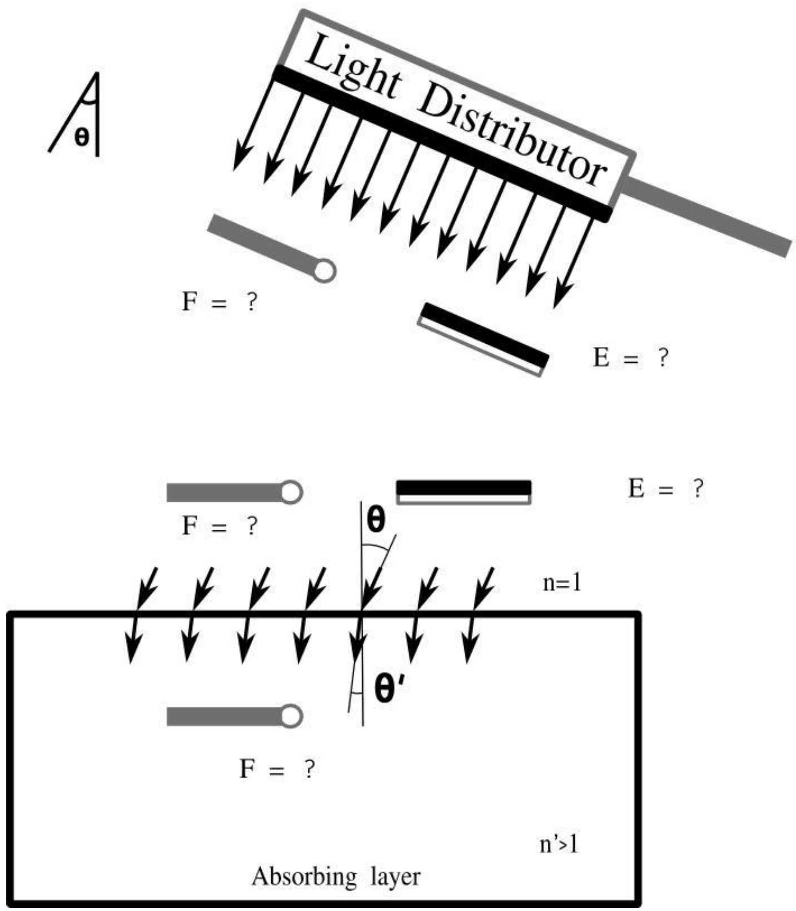
and $\frac{dr'}{d\theta} = \frac{1}{\cos^2\theta} \cdot h$

$$dS = h \cdot \tan\theta \cdot \frac{h}{\cos^2\theta} d\theta \, d\varphi$$

$$\int \cos\theta \cdot \tan\theta \; d\theta = -\cos\theta$$

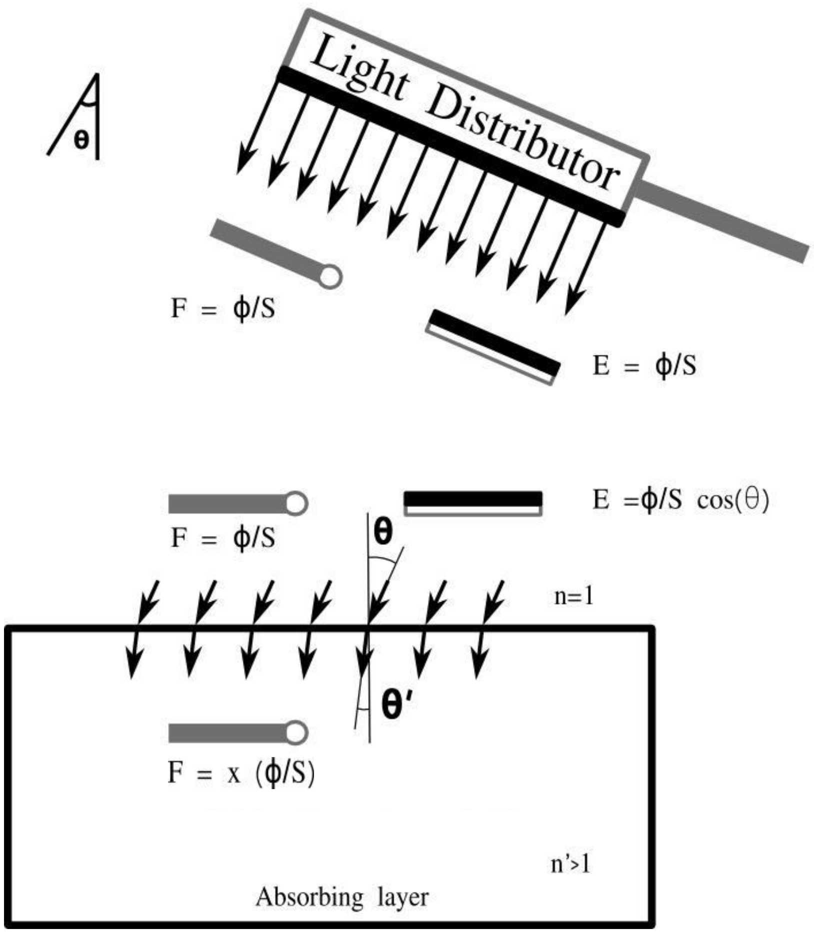
Case 5

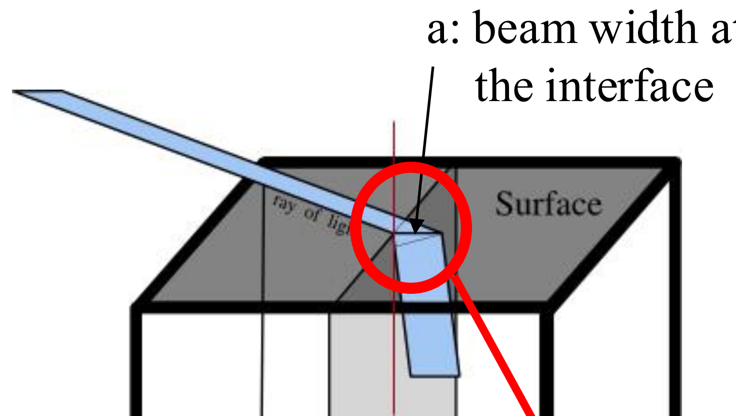
Laser power [W]: ϕ
Distributor surface [m^2]: S



Case 5 (solution)

Laser power [W]: ϕ
Distributor surface [m^2]: S

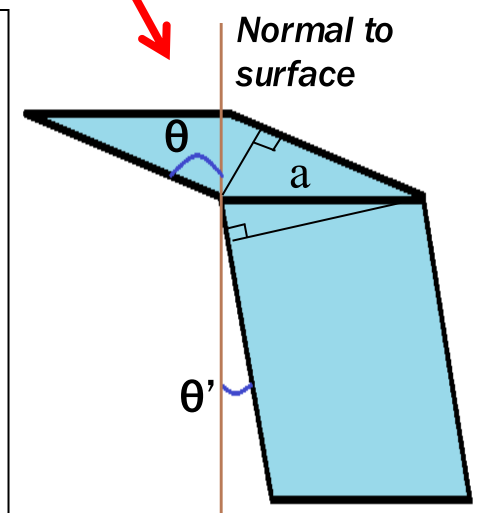




$$\begin{cases} x = \dfrac{a\cos(\theta)}{a\cos(\theta')} \\ n\sin(\theta) = n'\sin(\theta') \end{cases}$$

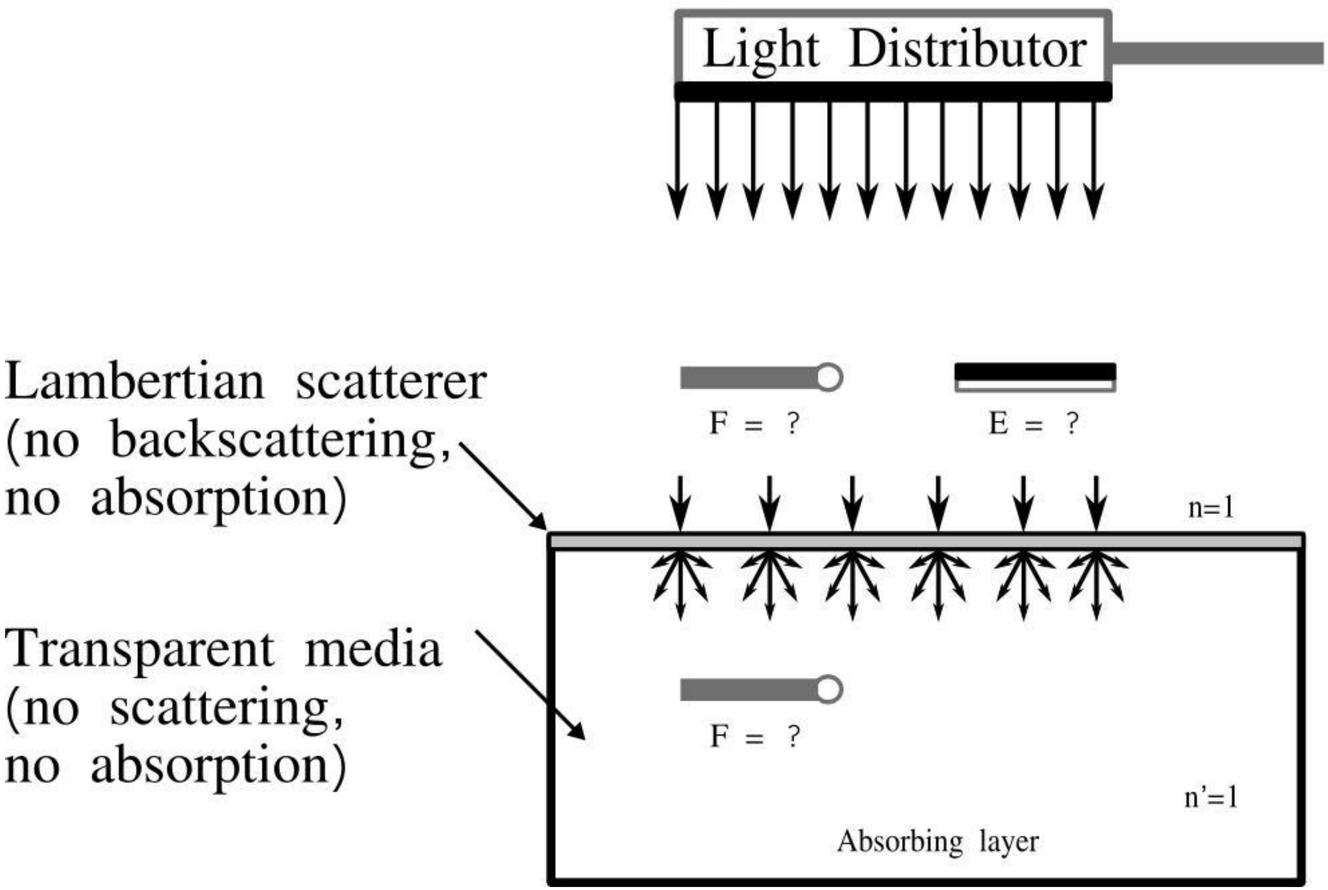
$$F = \frac{\phi}{S}x$$

$$x = \frac{\cos(\theta)}{\cos(\arcsin[(\frac{n}{n'})\sin(\theta)])}$$



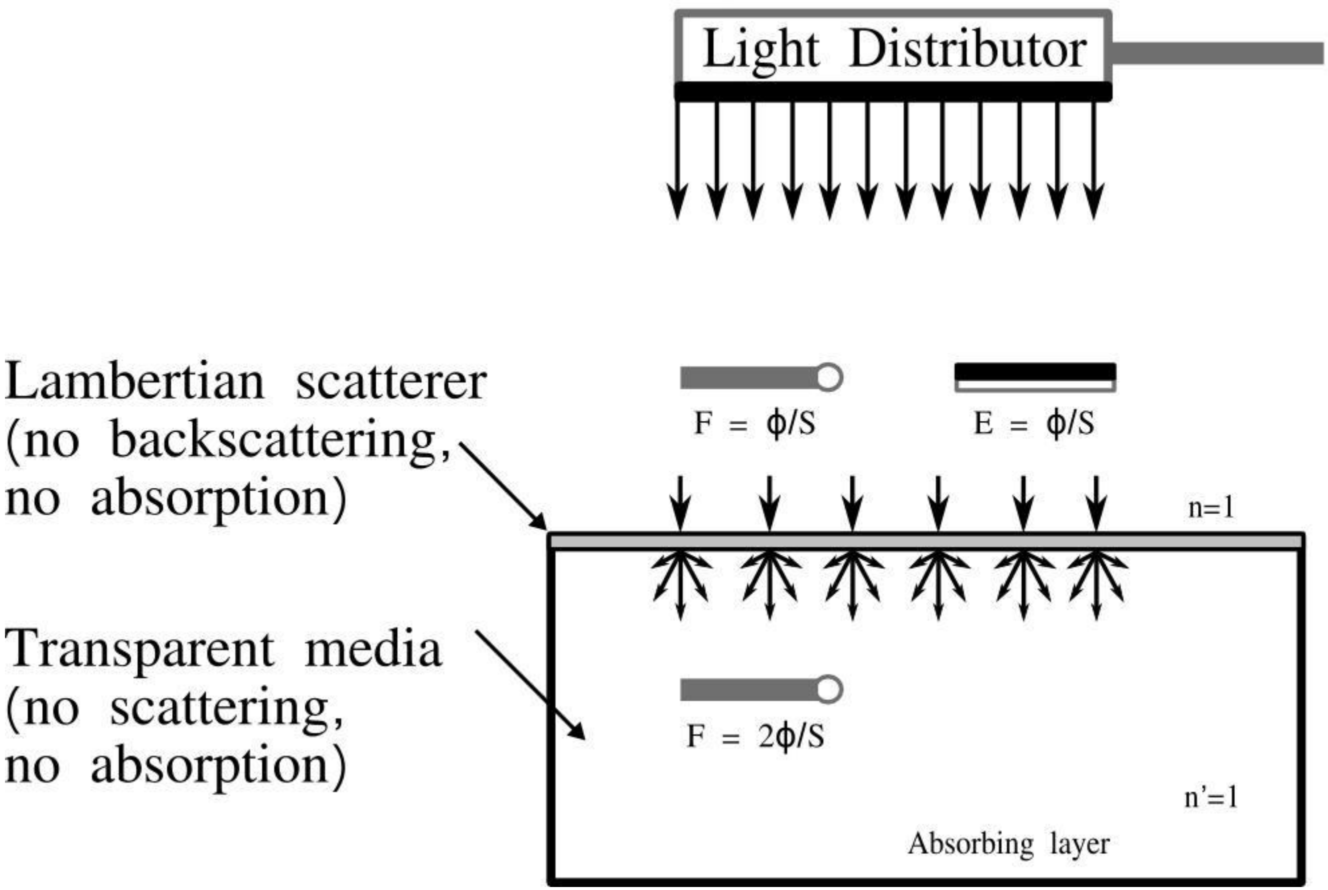
Case 6

Laser power [W]: ϕ
Distributor surface [m^2]: S



Case 6 (solution)

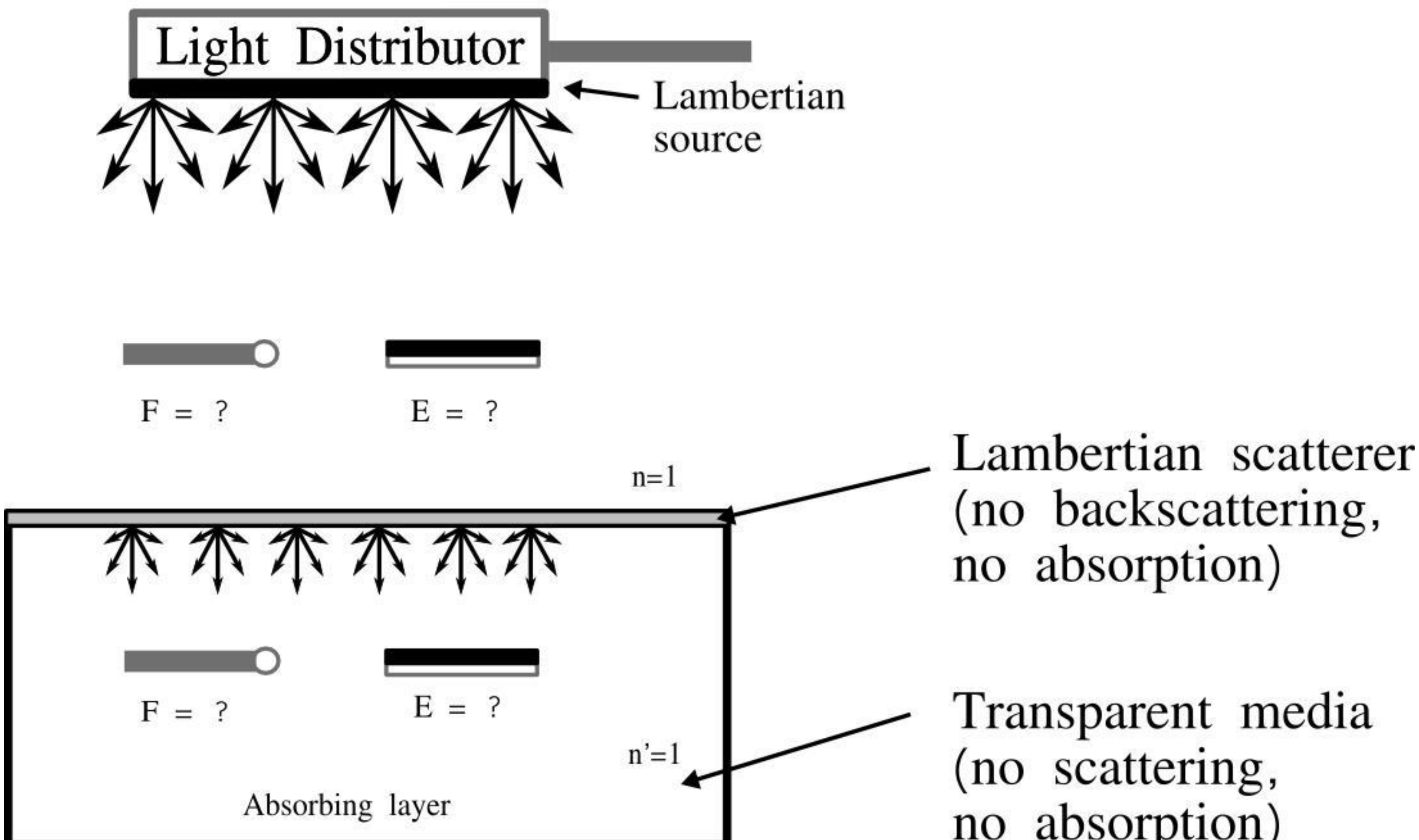
Laser power [W]: ϕ
Distributor surface [m^2]: S



Case 7

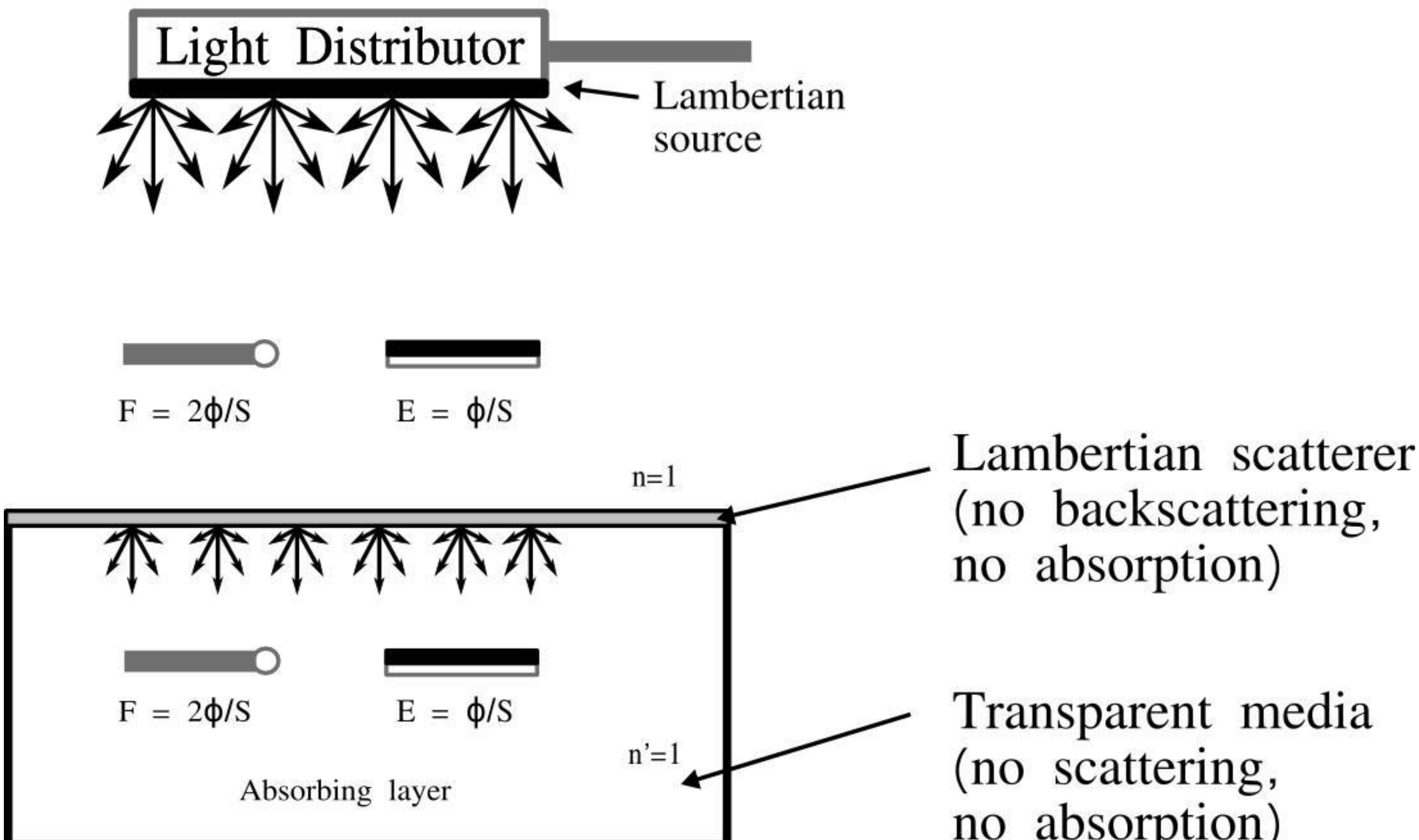
Laser power [W]: ϕ

Distributor surface [m^2]: S



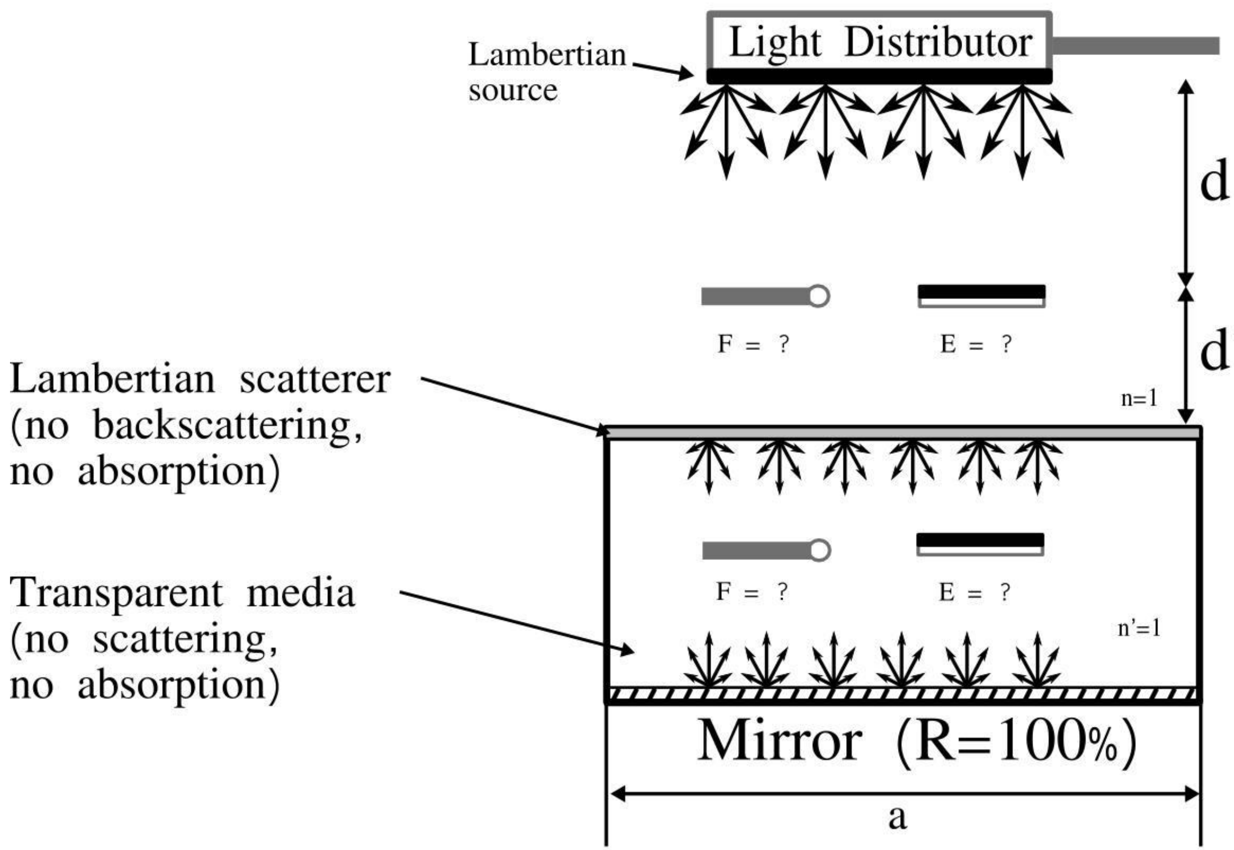
Case 7 (solution)

Laser power [W]: ϕ
Distributor surface [m^2]: S



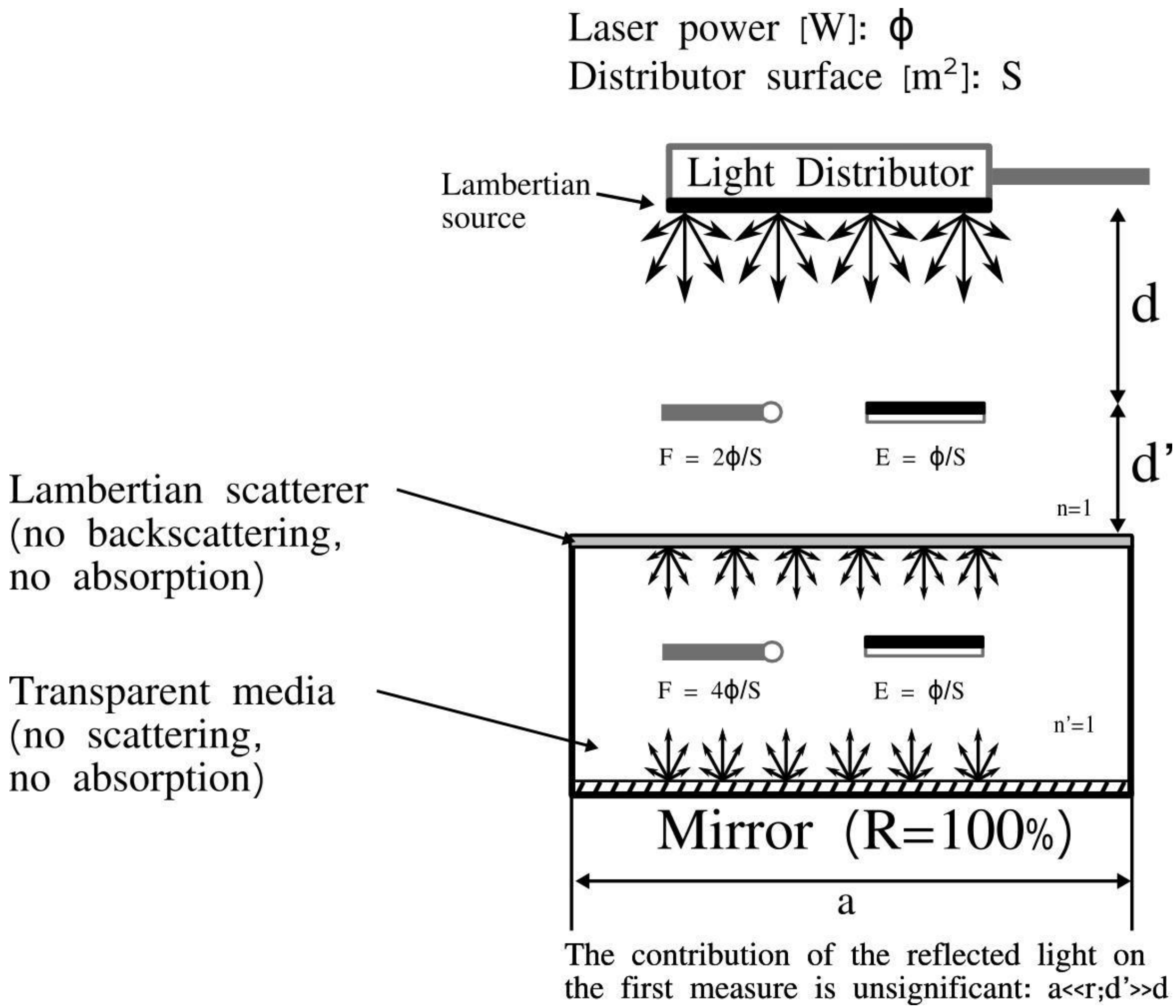
Case 8

Laser power [W]: ϕ
Distributor surface [m^2]: S



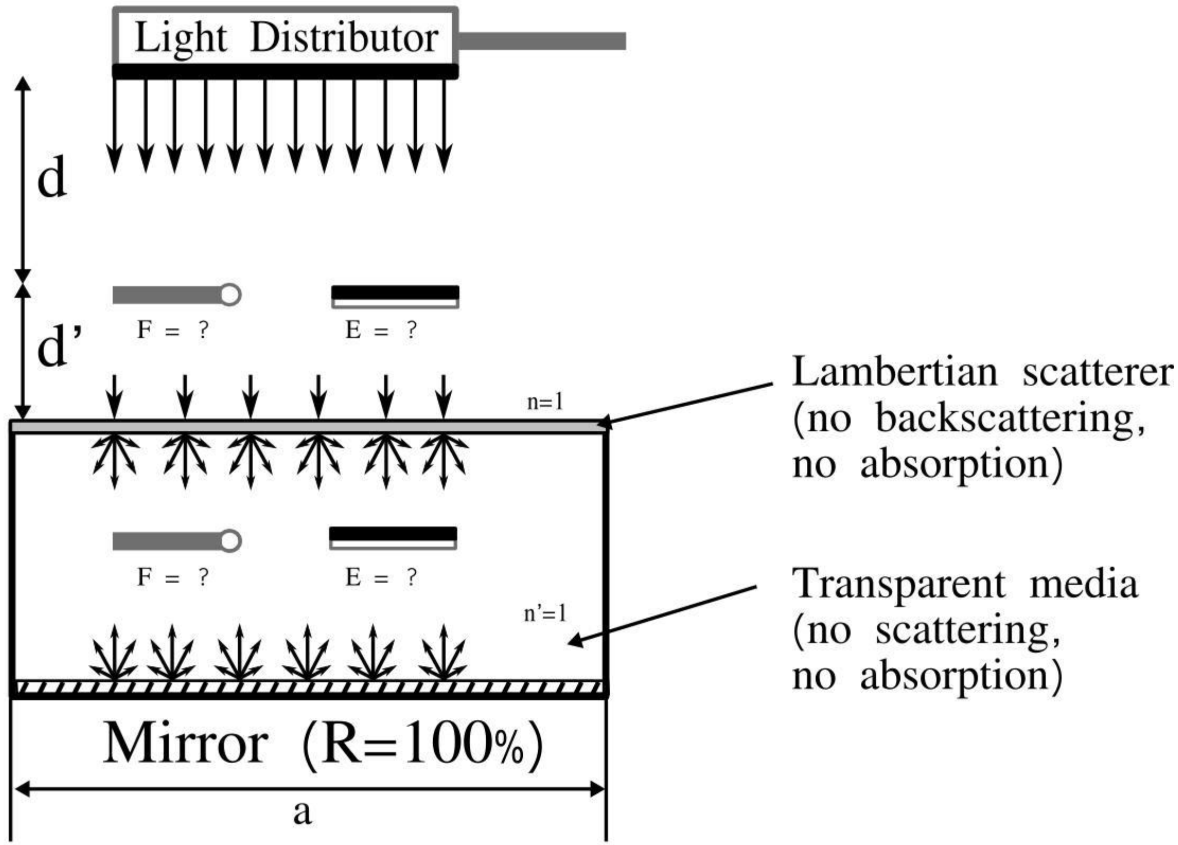
The contribution of the reflected light on the first measure is unsignificant: a<<r;d'>>d

Case 8 (solution)



Case 9

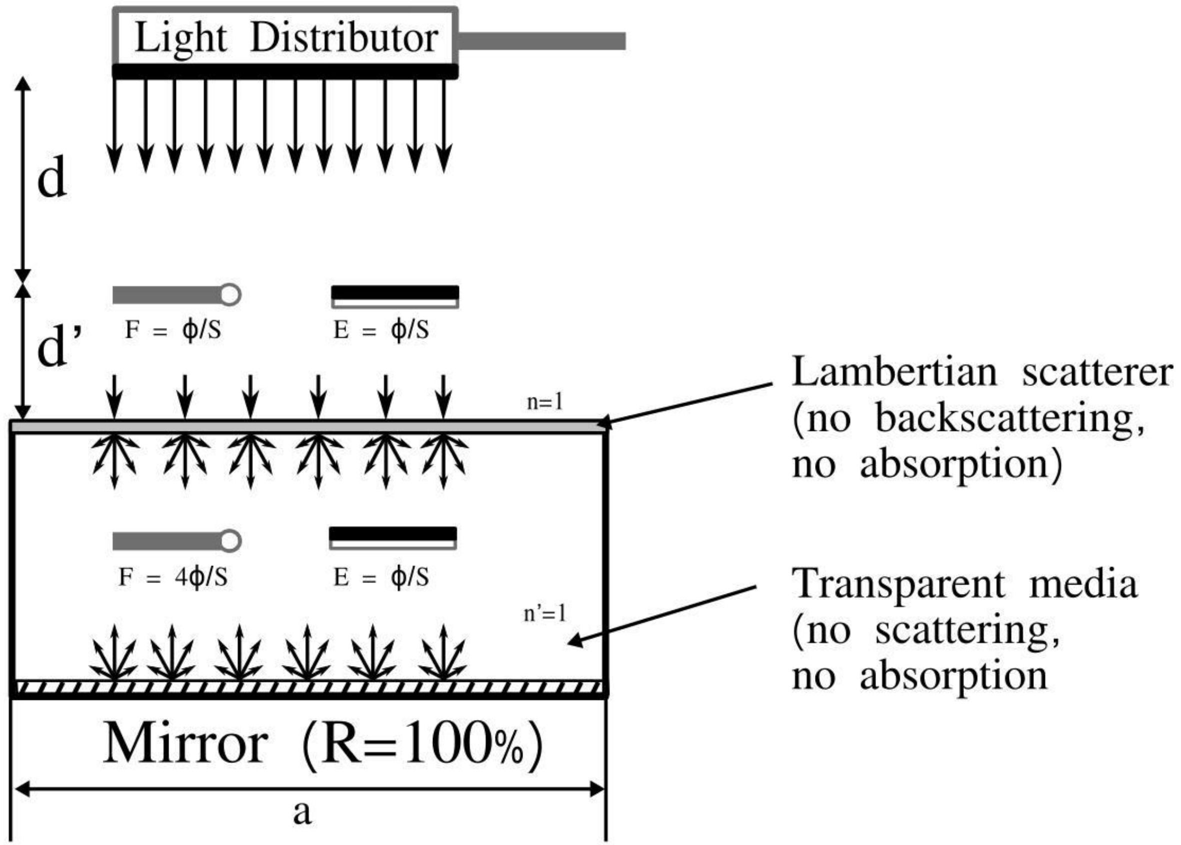
Laser power [W]: ϕ
Distributor surface [m^2]: S



The contribution of the reflected light on the first measure is unsignificant: a<<r;d'>>d

Case 9 (solution)

Laser power [W]: ϕ
Distributor surface [m^2]: S



The contribution of the reflected light on the first measure is unsignificant: a<<r;d'>>d