Dipartimento INFOCOM
Università degli Studi di
Roma “La Sapienza”

Departamento de Señales y
comunicaciones
ULPGC

Optical Communications

Telecommunication Engineering
School of Engineering
University of Rome La Sapienza
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- Instructor

  Maria-Gabriella Di Benedetto
  Professor
  Infocom Dept.
  dibenedetto@newyork.ing.uniroma1.it
  http://acts.ing.uniroma1.it

- Teaching assistant

  Luca De Nardis
  Infocom Dept.
  lucadn@newyork.ing.uniroma1.it

- Contact information

Course mailing list: oc@newyork.ing.uniroma1.it
Course web page: http://wsfalco.ing.uniroma1.it/02-courses-trasmissioni_ottiche.html

Thanks to:

Rafael Perez-Jimenez
Professor
Signals and Communications Dept.
University of Las Palmas Gran Canaria,
Spain

Program Course

Fondamenti di un sistema di comunicazioni ottiche

- Introduzione
  - Unità e grandezze
  - Concetti di base: introduzione all’ottica, budget di potenza
- Blocchi costituenti di un sistema di comunicazioni ottiche
  - Emettitori
  - Ricevitori
  - Caratterizzazione del rumore
- Modulazione e codifica
- Strategie di multiplazione e controllo di accesso al mezzo (MAC)

Il canale su fibra ottica

- La fibra ottica
- Reti e sistemi

Comunicazioni ottiche a infrarossi

- Analisi del canale indoor
- Standards e applicazioni

Introduction

INDEX

1. Introduction

- What are optical communications?
- Magnitudes, units and ranges
- Basic concepts
  - introduction to optics
  - power and time budgets

HISTORICAL PERSPECTIVE

The Semaphore Telegraph (1793)

1793: Claude Chappé: the semaphore telegraph

The semaphore telegraph is an optical telegraph. Two arms could assume 7 different positions. The connecting bar could assume 4 different positions for a total of 7x7x4=196 configurations
First recorded use of the term *telegraph*: "far writing"

Claude Chappe
(1763-1805)

1855: Jules Leseurre: the mirror heliograph

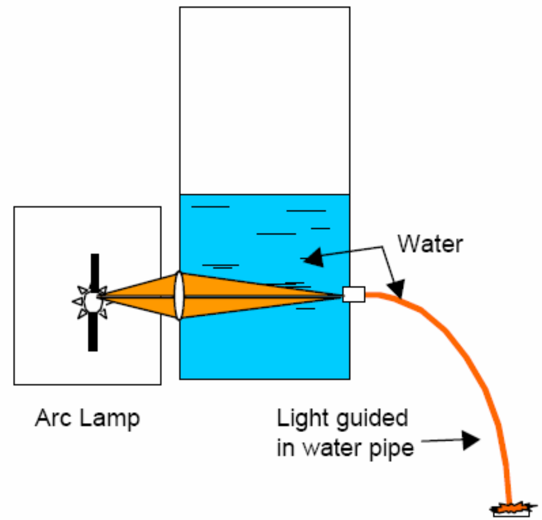
A British Mark V Mance pattern 5-inch heliograph.

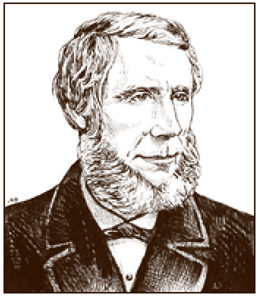
The heliograph sends signals by reflecting sunlight towards the intended recipient on mirrors.
The beam is keyed on and off by a shutter or by tilting mirrors, allowing thus Morse coding.
Heliographs were used by the armies of several countries during the late 1800's.
Speed was 5 to 12 words per minute, depending on Morse skills of the operators.

HISTORICAL PERSPECTIVE

1841: Daniel Colladon

First attempts at guiding light on the basis of total internal reflection in a medium. Colladon attempted to couple light from an arc lamp into a stream of water.





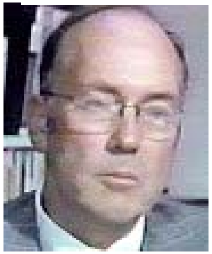
John Tyndall

1854: John Tyndall

Tyndall demonstrated that sun light can be guided by a curved stream of water

1958: Charles H. Townes & Arthur L. Schawlow; laser theory

Townes invented the microwave-emitting maser in the early 1950s at Columbia University. With postdoctoral student Schawlow he co-authored the paper "Infrared and Optical Masers," published in December 1958, *Physical Review.*



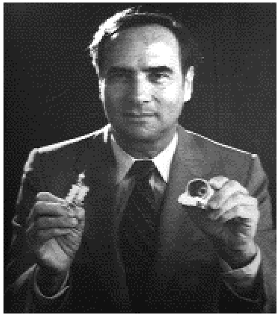
Charles H. Townes

1964 Nobel Prize

Arthur L. Shawlow

1981 Nobel Prize

HISTORICAL PERSPECTIVE



Theodore H. Maiman

1960: Theodore H. Maiman; optical Laser

The optical Laser consisted of a ruby crystal surrounded by a helicoidal flash tube enclosed within a polished aluminum cylindric cavity

1966: Charles Kao; Low-loss glass guidance

Proposed fiber as an alternative to existing wired transmission media

Charles Kao

1961: Elias Snitzer; theoretical basis for very thin (several micron) fibers, which are the foundation for our current fiber optic communication networks. The notion of launching light into thin fibers was suggested by **von Karbowiak in 1963**

Ruby Laser Systems
Patent Number(s) 3,353,115

1967: S. Kawakami (graded-index fiber). Fiber with index of refraction varying in a continuous, parabolic manner from the center to the edge

1976 First practical installation of a fiber : Chicago, IL, USA in 1976.

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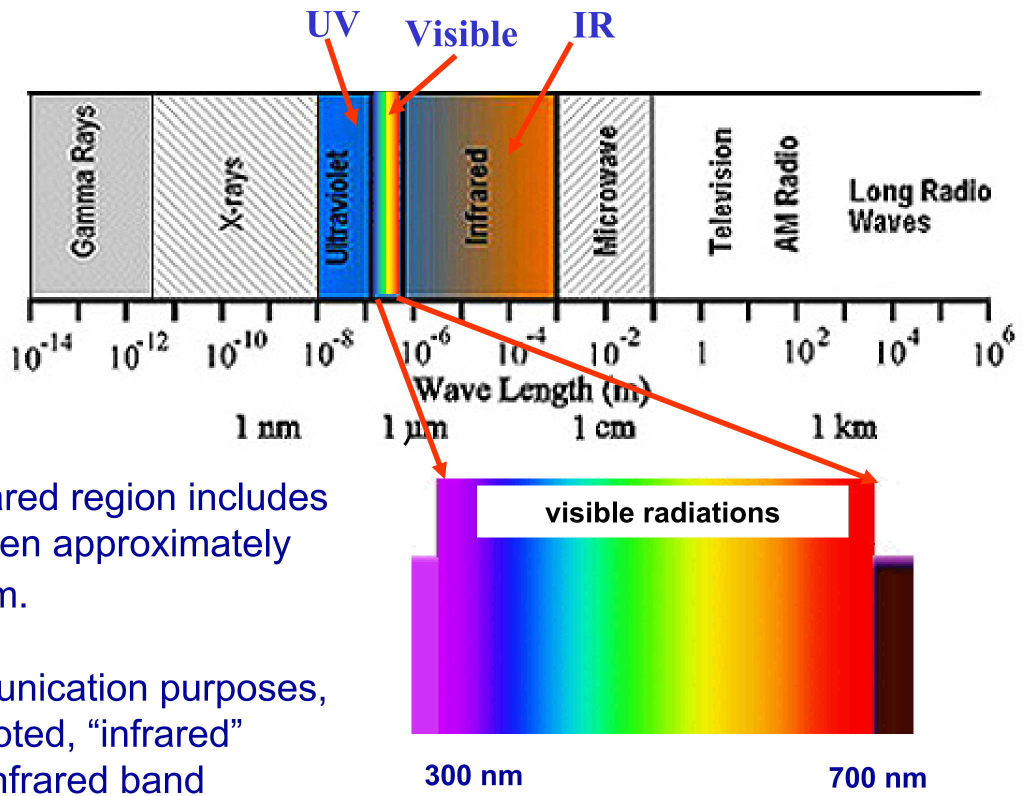
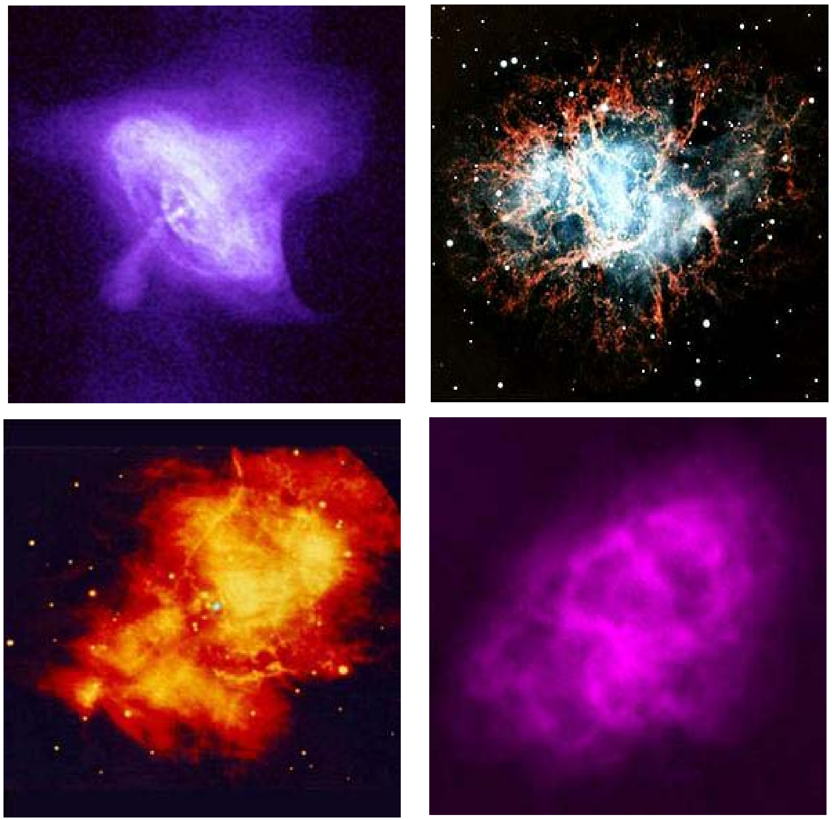
MAGNITUDES: OPTICAL SPECTRUM



In general, the infrared region includes wavelengths between approximately 700 nm and 100 µm.

For wireless communication purposes, unless otherwise noted, “infrared” refers to the near-infrared band between about 780 nm and 1.6 µm.

MAGNITUDES: OPTICAL SPECTRUM



Using different sensors (commonly with band-pass filters) each tuned to accept and process the wave frequencies (wavelengths) that characterize each spectrum region, will normally show significant differences in the distribution of the perception of the same object.

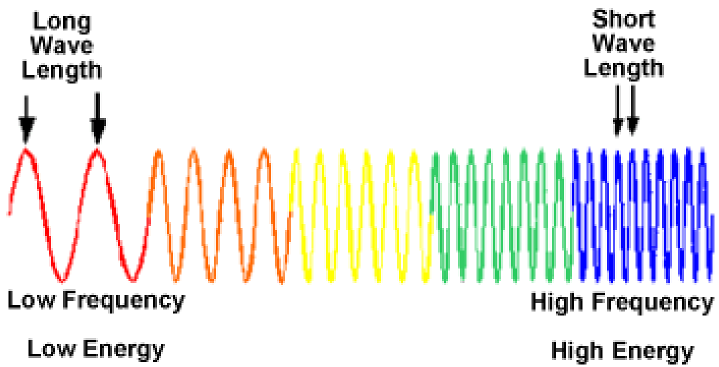
The upper left illustration shows the Nebula in the high energy x-ray region; the upper right is a visual image; the lower left was acquired from the infrared region; and the lower right is a long wavelength radio telescope image.

Source: NASA

PHOTONS AND SPEED OF LIGHT

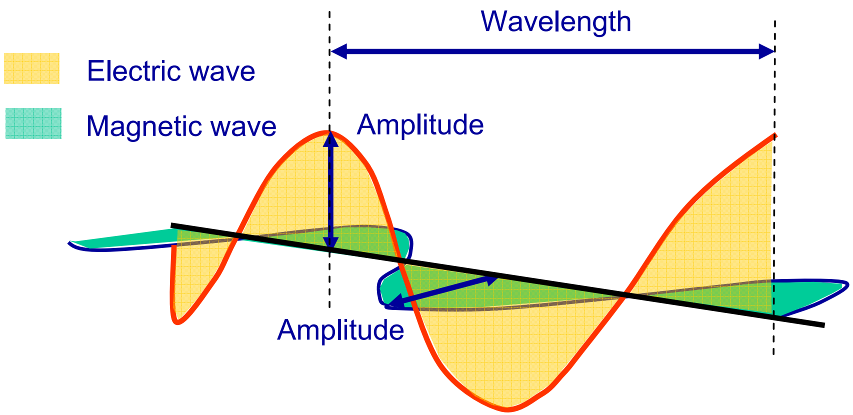
The photon is the physical form of a quantum of light. It is described as the messenger particle for the EM force or as the smallest bundle of light. This subatomic mass-less particle comprises radiation *emitted* by matter when it is excited thermally, or by nuclear processes (fusion, fission), or by bombardment by other radiation. It also can become involved as *reflected* or *absorbed* radiation.

Photons move at the speed of light: 299,792.46 km/sec (commonly rounded off to 300,000 km/sec or ~186,000 miles/sec). These particles also move as waves and hence, have a "dual" nature. These waves follow a pattern that we described in terms of a sine wave function.



PHOTONS: WAVE NATURE

A photon travels as an EM wave having two components: the electric field and the magnetic field. The two components travel as sine waves along orthogonal planes. Both have same amplitude (strength) and reach their maxima-minima at the same time. **Photon waves can transmit through a vacuum** (such as in space). When photons pass from one medium to another, e.g., air to glass, their wave pathways are bent, that is they follow new directions and thus experience **refraction**.



PHOTONS: QUANTIZATION

A photon is said to be quantized, since a photon is characterized by a fixed quantity of energy. Different photons may have different energy values. Photons thus show a wide range of discrete energies. The amount of energy characterizing a photon is determined using Planck's general equation:

$$E = h \cdot f$$

h is Planck's constant (6.6260... x 10^{-34} Joules▪sec)
f is frequency

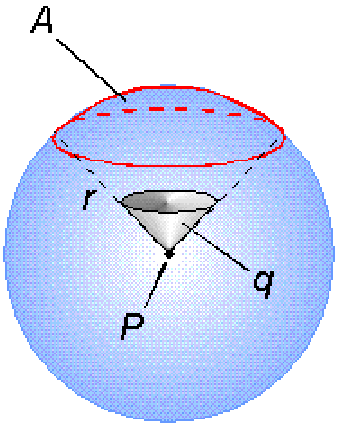
Photons traveling at higher frequencies are therefore more energetic. If a material under excitation experiences a change in energy level from a higher level E_2 to a lower level E_1, we restate the above formula as:

$$\Delta E = E_2 - E_1 = h \cdot f$$

where *f* has a discrete value determined by (f_2 - f_1). In other words, a particular energy change is characterized by producing emitted radiation (photons) at a specific frequency *f* and a corresponding wavelength at a value depending on the magnitude of the change.

UNITS: STERADIAN

Steradian (sr): Standard International unit of solid angular measure in mathematics. There are 4π, or approximately 12,5664, steradians in a complete sphere. A steradian is defined as conical in shape. Point *P* represents the center of the sphere. The solid (conical) angle *q*, representing one steradian, is such that the area *A* of the subtended portion of the sphere is equal to r^2, where *r* is the radius of the sphere.



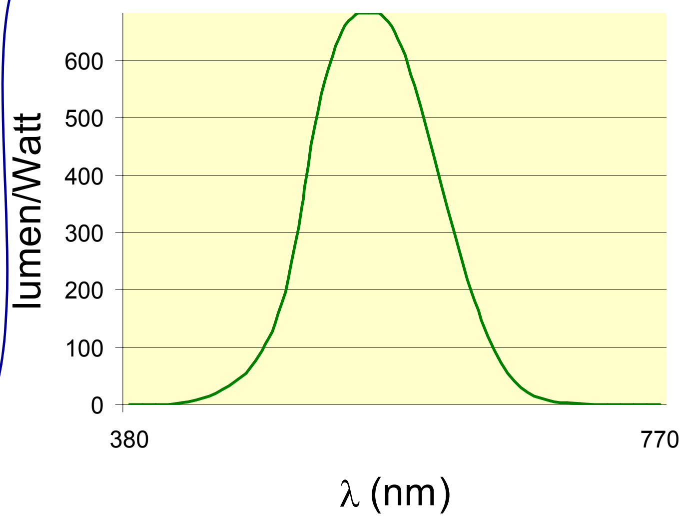
A general sense of the steradian can be envisioned by considering a sphere whose radius is r =1m. The total surface area of the sphere is, in this case: 12,5664 square meters (=4πr^2).

RADIANT AND LUMINOUS FLUX

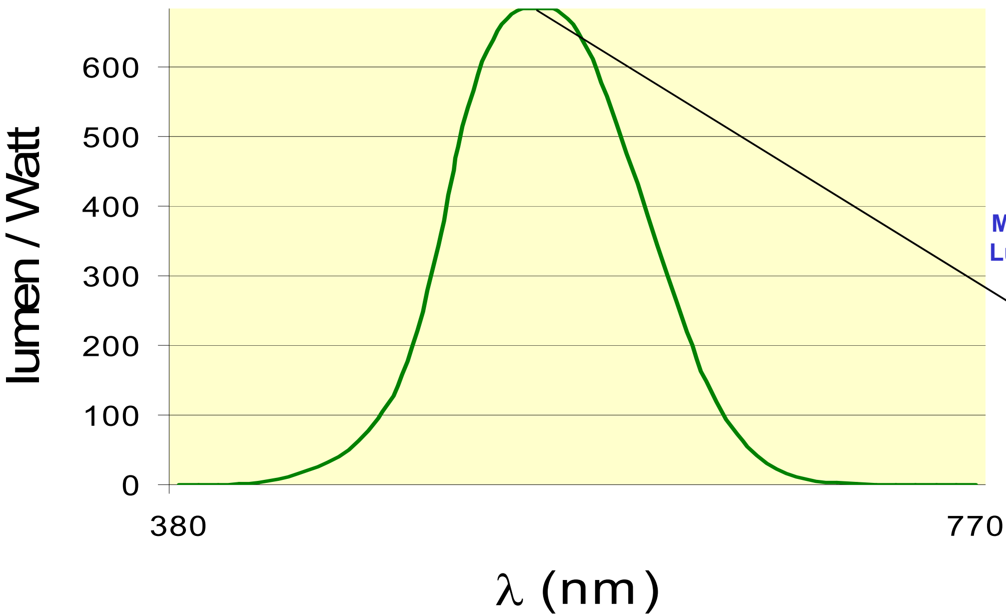
Radiant flux is a measure of radiometric power. Radiant flux, expressed in **Watts (W)**, is a measure of the rate of energy flow, in **Joules/second**.
Luminous flux is a measure of power of "visible" light, that is light power as perceived by a human. The unit of measure is the **lumen (lm).**

The difference between **lumen** and **Watt** is that lumen is a unit of the **photometric** system, while Watt belongs to the **radiometric** system.
Both characterize the power of a light flow. However, lumen is power "related" to the human eye sensitivity. Therefore, lights with the same power in watts, but different colours have different luminous fluxes, because the human eye has different sensitivity at different wavelengths.
A radiation with 1 Watt in the infrared region has no luminous flux.

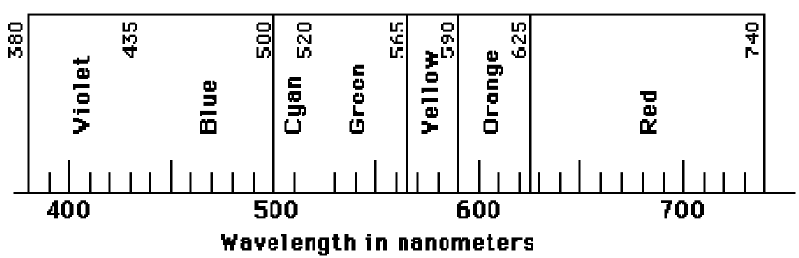
At a wavelength λ of 555 nm (maximum eye sensitivity) 1 Watt = 683 lm



RADIANT AND LUMINOUS FLUX



Color	Wavelength λ (nm)	Luminous Flux lm/W
---	380	0.02
Violet	410	0.82
Blue	470	62.13
Cyan	510	343.5
Green	540	651.5
MAX	**555**	**683**
Yellow	570	650.2
Orange	610	343.5
Red	700	2.80
---	770	0.02



RADIANT AND LUMINOUS INTENSITY

Radiant intensity: measure of radiometric power of an optical source per unit solid angle, expressed in watts/steradian (W/sr).
Luminous intensity (or **candlepower**): is the light density, this is a measure of luminous flux per unit of solid angle. The unit of measure is **candela (lm/sr)**.

Candela (cd) is the SI unit for measuring the intensity of light.

- current definition: the luminous intensity of a light source producing single-frequency light at 540 THz (1 THz = 10^{12} Hz) with a power of 1/683 W/sr, or 18.3988 mW over a complete sphere centered at the light source. The frequency of 540 THz corresponds to a wavelength λ of approximately 555.17 nm.
- in order to produce 1 candela of single-frequency light at wavelength λ, a lamp would have to radiate **$1/(683 \cdot V(\lambda))$ W/sr**, where $V(\lambda)$ is the "normalized to one" sensitivity of the eye at wavelength λ. These values are defined by the CIE (COMMISSION INTERNATIONALE DE L'ECLAIRAGE).
- one **lumen** may be defined as the luminous flux emitted per steradian by a one-candela uniform-point source. In fact, one lumen equals to the intensity in candelas multiplied by the solid angle in steradians into which the light is emitted.
- thus, the total flux of a 1 candela light, if <u>light is emitted uniformly in all directions</u> (isotropic), is 4π lumens

IRRADIANCE AND ILLUMINANCE

Irradiance is a measure of radiometric flux per unit area, or flux density. Irradiance is typically expressed in W/cm^2 or W/m^2

Illuminance is a measure of photometric flux per unit area, or visible flux density.

Lux (lx) is the SI unit for measuring the illuminance of a surface.

• 1 lux is defined as an illuminance of 1 lm/m^2.

• As the intensity of the light source is measured in candelas; the total light flux in transit is measured in lumens (1 lm = 1 cd·sr); and the amount of light received per unit of surface area is measured in lux (1 lux = 1 lm/m^2 = 1 $cd{\cdot}sr/m^2$).

Phot (ph) is the CGS-system unit of illuminance, equal to 1 $lumen/cm^2$ or 10^4 lux.

LUMINANCE OR BRIGHTNESS

Luminance or **Brightness** is a luminous intensity on a surface **in a given direction** per unit of area of the surface. It can be measured in cd/m^2 (equivalent to $lm/sr/m^2$.)

A Lambertian surface area hit by an illuminance of π $lumens/m^2$ has a luminance of 1 cd/m^2

A **lambertian surface** i.e.diffuse reflector ideal is a surface that adheres to *Lambert cosine law*.
Lamberts cosine law states that the reflected or transmitted *luminous intensity* in any direction from an element of a perfectly diffusing surface varies as the cosine of the angle between that direction and the *normal vector* of the surface. As a consequence, the *luminance* of that surface is the same regardless of the viewing angle. A good example is a surface painted with a good "matte" or "flat" white paint.

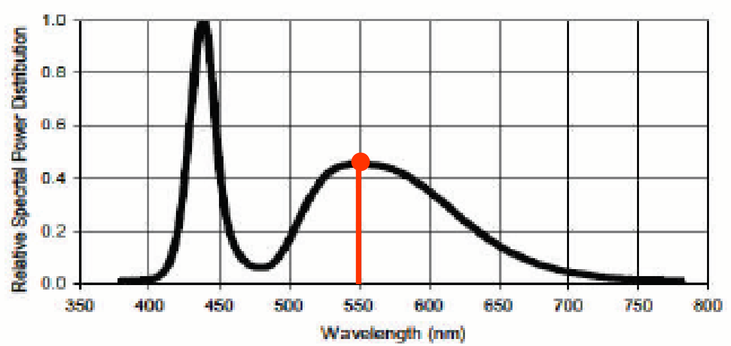
Lambert (La) is the CGS unit of luminous intensity of a surface, measuring the intensity of the light emitted (or reflected) in all directions per unit of area of the surface.

1 lambert is the luminance of a surface that is hit by one $lumen/cm^2$ that is 10^4 $lumen/m^2$ and thus

1 lambert= $10^4/\pi$ cd/m^2 = 3183.099 cd/m^2

EXAMPLE 1

Lambda	LEDchip+phosphor Relative spectral power distribution	LEDchip+phosphor spectral power distribution (normalized to 1 W/sr)
400	0,01	2,30E-03
420	0,2	4,59E-02
440	1	2,30E-01
460	0,158	3,63E-02
480	0,067	1,54E-02
500	0,167	3,84E-02
520	0,366	8,41E-02
540	0,45	1,03E-01
560	0,459	1,05E-01
580	0,419	9,63E-02
600	0,35	8,04E-02
620	0,261	6,00E-02
640	0,182	4,18E-02
660	0,116	2,66E-02
680	0,067	1,54E-02
700	0,036	8,27E-03
720	0,022	5,05E-03
740	0,01	2,30E-03
760	0,008	1,84E-03
780	0,005	1,15E-03
800	0	0,00E+00



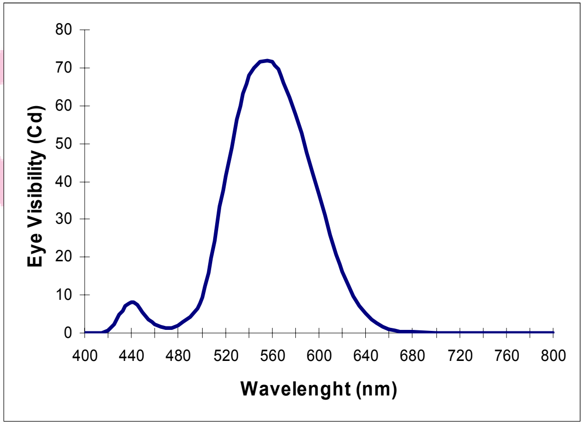
Relative spectral power distribution of the LEDchip+phosphor (corresponds to LXHLPW01 from LUXEON)

EXAMPLE 1

Lambda	Relative eye visibility V(λ)
400,00	2,44686E-03
420,00	2,04713E-02
440,00	5,17432E-02
460,00	8,80858E-02
480,00	1,84273E-01
500,00	3,56376E-01
520,00	7,29193E-01
540,00	9,61706E-01
560,00	9,94196E-01
580,00	8,79700E-01
600,00	6,64838E-01
620,00	3,99149E-01
640,00	1,81513E-01
660,00	6,20256E-02
680,00	1,67813E-02
700,00	3,89344E-03
720,00	8,76778E-04
740,00	2,05890E-04
760,00	5,18361E-05
780,00	1,38285E-05
800,00	3,91935E-06

Lambda	(LEDchip+phosphor Relative power distribution)*(Eye visibility expressed in candelas)
400,00	3,84E-03
420,00	6,42E-01
440,00	8,12E+00
460,00	2,18E+00
480,00	1,94E+00
500,00	9,34E+00
520,00	4,19E+01
540,00	6,79E+01
560,00	7,16E+01
580,00	5,78E+01
600,00	3,65E+01
620,00	1,63E+01
640,00	5,18E+00
660,00	1,13E+00
680,00	1,76E-01
700,00	2,20E-02
720,00	3,03E-03
740,00	3,23E-04
760,00	6,51E-05
780,00	1,08E-05
800,00	0,00E+00
Area	321

Then, a white LED with a radiant intensity of 1 W/sr has an optical intensity of 321 cd.



FURTHER READING

1. Additional information on the use of optical telegraph can be found at:

   http://en.wikipedia.org/wiki/Optical_telegraph

2. A useful tutorial on light properties and measurement units can be downloaded at the address:

   http://www.intl-light.com/ildocs/handbook.pdf