General Lighting Technology – Basics

Light is life – its energy makes our presence on earth possible in the first place.

But light is also philosophy and art, rouses emotions and generates moods.

How can we capture this phenomenon? Can it be explained, defined, measured?

Light is difficult to explain even by help of theoretical physics. Moving on to the practical side of qualitative and quantitative collection, things get even more difficult. With every further step of technology, these problems get easier and better to solve.

When subjective impressions add on, one and the same actual facts or lighting situation, respectively, can be valued completely differently. That makes things complicated but also very interesting.

Good light – good lighting – does not catch the eye, but whenever good light is missing the atmosphere is kind of wrong, one does not feel good. This is intuitive knowledge.

The concept of good lighting in contradiction to that, needs sound standing proficiency of lighting technology. The basics thereof are quoted in this Radium Lichtbrief (light letter).

What is Light?

Light is the wave lengths or frequency range of electromagnetic radiation which can be received by the eye, i.e. can be seen.

Relationship between wave length (λ) and frequency (f):

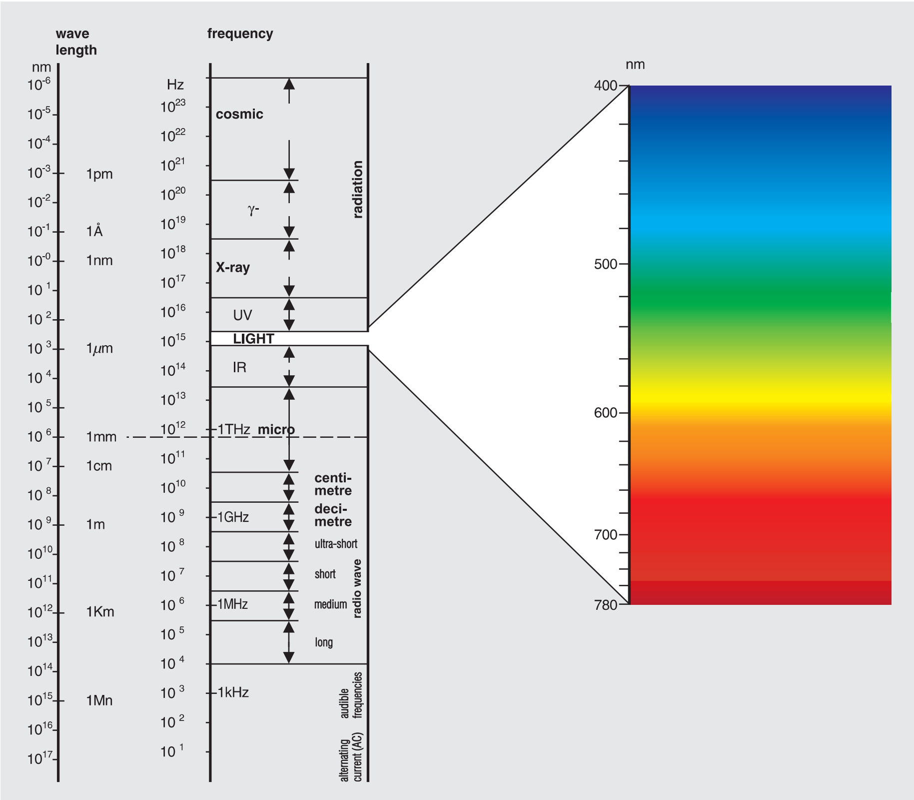
$$\lambda = \frac{c}{f}$$

The propagation velocity c of this radiation is constant within vacuum and constitutes to about 300,000 km/s.

Light velocity in vacuum:
c = 299 792 458 m/s

The radiation spectrum of visible white light – like light of incandescent lamps or daylight at noon of a sunny day – consists of single coloured (monochromatic) fractions of radiation. These are allocated to certain wave lengths which reach from violet at about 380 nm (1nm = 10^{-9} m) to dark red at 780 nm.

The short-waved UV-radiation, visible light and long-waved infrared radiation can be called ‘optical radiation’ altogether.



Electromagnetic radiation
Light is only a small part of the natural electromagnetic radiation

Perception of light

Biological sensor technology

The eye is the organ by which higher developed creatures can perceive light. In this process, the sensitivity of the sensor is not the same always: identical radiation powers in different wave lengths are observed differently. So, a human eye senses green-yellow light especially bright, on the other hand, short-waved blue light at the same radiation power only quite weak.

To the contrary, insects see within long-wave UV and the adjacent blue range very well, yellow, however, is quite bad. Furthermore, eye sensitivity differs individually, too, but there are mean values which can and have to be used as orientation by technology.
Due to this biological component absolute measurements in the domain of lighting are much more difficult than cases in classical physics.

Whereas a length in meters or millimetres can be given very exactly, meaning with small tolerances, lighting technology must live with bigger tolerance ranges: How bright is bright?

Eye and process of sight

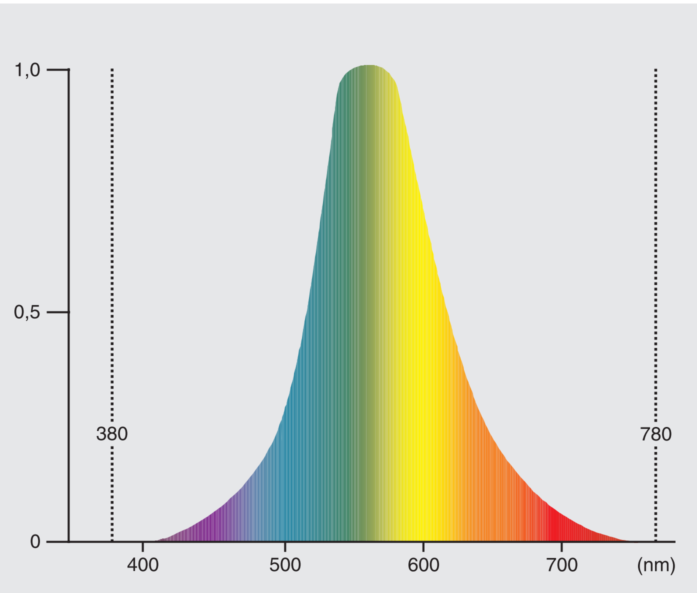
Electromagnetic radiation of certain wave lengths is perceived by the human being as light, only if enough radiation power gets onto the retina of the eyes and there are ready receptors available.
As this eye sensitivity is different for the various wave lengths the perception of brightness varies even at the same radiation power.

On average, the eye is adapted to light when lighting is good (day), i.e. at high illuminance. With this photopic vision the 3 kinds of cones on the retina are active – they are the receptors for red, green and blue which makes them responsible for coloured vision. Then, the curve of eye sensitivity follows the so-called V(λ)-function which has got its maximum at about 555 nm.
In actual fact, every kind of cone has got its own sensitivity curve:

red x (λ), green y (λ), blue z (λ)

For practical use, with sufficient accuracy the curve of their mean values V(λ) equals the green curve y (λ).

When light gets low (at night) the eye is dark adapted.



Eye sensitivity curve
The eye perceives equal radiation powers differently at different wave lengths

With scotopic vision the light-dark perception dominates, which is controlled by the rods on the retina.

The eye sensitivity curve moves as V'(λ) into a more short-waved range and then has got its maximum at about 507 nm. In the mesopic zone (twilight) between day and night vision the eye cannot align clearly, therefore, many human beings have got optic difficulties.

Light and Colour

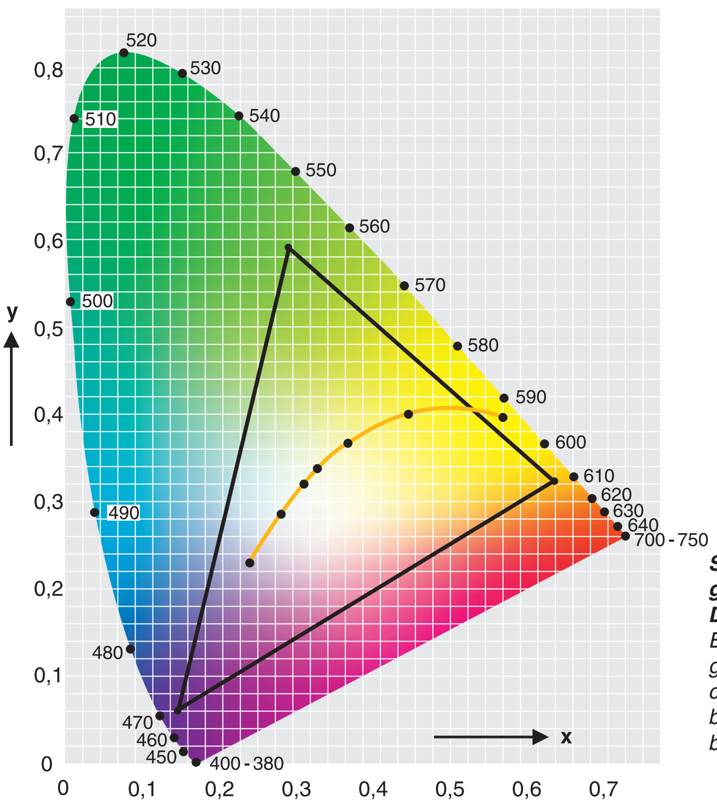
The human eye evaluates incoming light not only according to the impression of brightness but also according to colours. The cones do something like additive colour mixing with the light impressions, so that finest differences can be detected.

If you do not take brightness into account, the x-, y- and z-curves are the so-called standard spectral power functions of a light source and always sum up to 1. Therefore, it is enough then to quote the measured x- and y-values of a light source in order to describe its colour. These values are shown in the standard colour graph.

As indicated by the laws of additive colour mixing, white light is generated if all colours are included in the same proportions. Therefore, the white point on the standard colour graph emerges at x = 0,333 and y = 0,333.

Colour temperatures – another way of describing the light colours – are to be found on Planck's curve and Judd's straight lines.

For light sources which do not have chromaticity coordinates on Planck but quite close, a so-called most similar colour temperature can be specified. Its value corresponds with the point of Planck's curve where the chromaticity coordinates of the light source are nearest (minimal distance).



Standard colour graph according to DIN 5033
Every light colour has got chromaticity coordinates and can be described exactly by those

The basic properties reflection, absorption and transmission can be different with different parameters:

Material structure and texture:
The more penetrable a material is for radiation, the more probable transmission becomes (e.g. clear glass vs. satin/ frosted glass)

Surface:
The smoother, the more probable reflection (e.g. mirror)

Angle of radiation:
For example, total reflection at water surface when looking at a flat angle

Spectral power:
Please, refer to colour rendering

Within the lighting business we live and work with that every day, for example when measuring light (in the Ulbricht sphere) or light transportation (through glass fibres) and also in light planning (surfaces in rooms), of course.

Light and Matter

Reflection – Absorption – Transmission

In order to see an object, light must fall on it, this light must be reflected by it and the get into the eye. Does an object let pass the light all in all or in parts – by technical term called transmission – this object appears translucent or transparent. Does the object, however, absorb the light fully or parts of it – absorption – it appears bright or dark, depending on how much light it has absorbed.

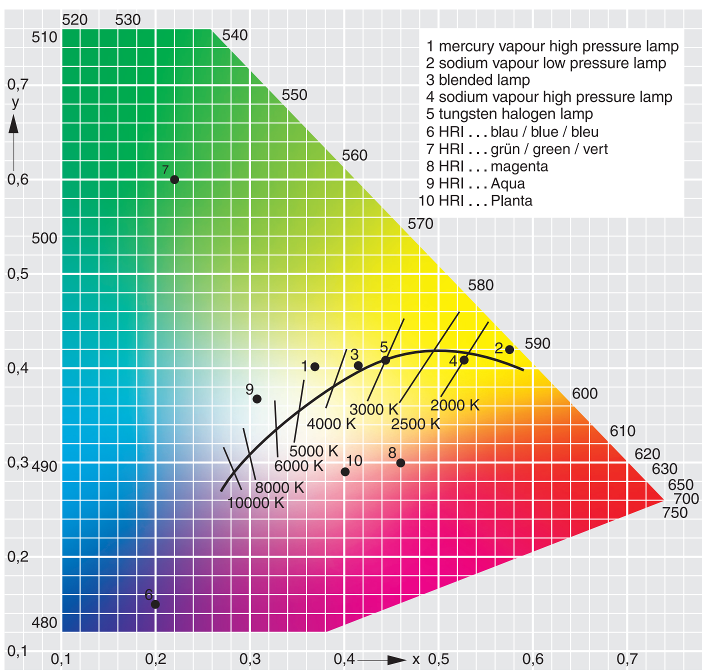
Colour Rendering

See colours as they really are

Not only light itself has got colour, by help of light the colours of the observed objects shall be visible. This can only be possible when in the spectral power distribution of the light source the corresponding wave lengths exist. Therefore, for perfect colour rendering only light sources with continuous spectral power distribution are suitable (like thermal radiators such as incandescent lamps). In other cases, the eye can perceive colours only with a change.

Example: Clothes Shopping

A shop is lighted by triphosphor fluorescent lamps, exclusively. A light grey pair of trousers and a light grey patterned shirt fit and match perfectly within the fitting room. At home surprise hits: when unpacking at daylight the trousers have got a hint of green and the shirt is in fact brownish with a hint of red.



Extract from the colour triangle
Positions of typical lamp light colours on the standard colour graph

Measurement and Colour Rendering Index

The colour rendering of a light source is assessed by a comparative measurement. In this process the reflective spectral power distributions (remission-spectrum) of 8 certain colours are measured twice: first, when lit by a standard light source and second when lit by the lamp to be valued. Additionally, the light colours of the two light sources shall be as similar as possible, the same at best.

These remission spectra are then compared in an elaborate computing process for every single colour. Are they identical, the colour rendering index Ra is 100. Is the colour change substantial, the colour rendering index can even become negative.

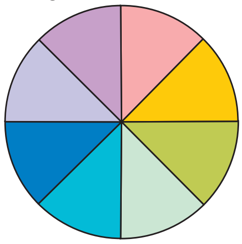
From the Ra-values of the single colours an all-over value can be established for the lamp to be valued. Additionally, colour rendering of another 6 colours (sometimes even 8) might be interesting for certain applications.

Colour Rendering and Colour Fastness

Colour rendering does not have anything in common with colour fastness or yellowing. Colour rendering means to be able to see colour as they really are. Colour fastness, to the contrary, means colours stay as bright as they have always been and do not yellow in spite of all the different ambient influences (light, heat, UV-radiation, humidity, chemicals, etc.).

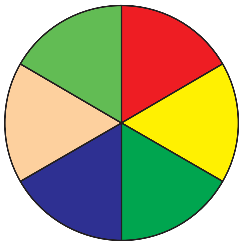
Colour Rendering R1-R8

Test colours 1-8:
Dusky pink
Mustard yellow
Yellow green
Light green
Turquoise blue
Sky blue
Aster violet
Lilac violet



Colour Rendering R9-R14

Test colours 9-14:
Red
Yellow
Green
Blue
Skin colour
Leaf green



Light Generation

Properties of Different Light Sources

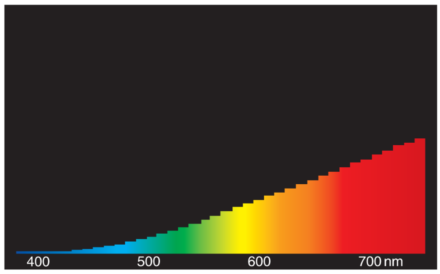
Thermal Radiation

A thermal radiator becomes so hot that it emits energy in the form of light such as fire or incandescent lamps.

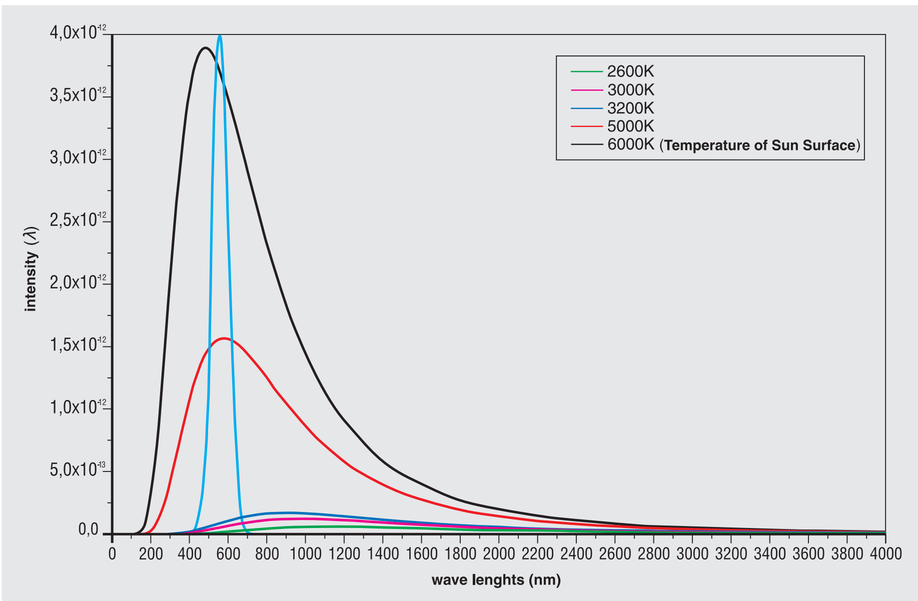
Thermal radiators have got continuous spectrum, i.e. they emit at all wave lengths. Which wave lengths are more and which ones are less included depends on the temperature of the radiator. So, with every change of temperature the distribution of radiation power within the spectrum changes.

Planck enunciated on the results of some predecessors (mainly Wien's displacement law) the theoretical physics' basics of light colours. That's how one can explain colour temperatures of light: a black body is heated up until it emits visible radiation – light.

The respective temperature of the body is taken for describing the corresponding light colour.



Spectrum Incandescent Lamp
Spectral power distribution of incandescent lamps

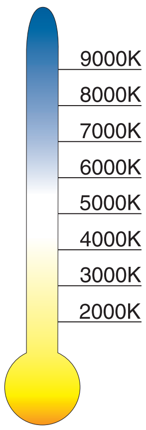


Planck Distribution Curve
Planck distribution curve for different 'black body temperatures'

Therefore, the rule applies – even if it seems illogic at first glance: because the body needs to be hotter for them, the **cold** (white) light colours have got higher colour temperature values than the **warm** (yellow-red) ones.

Hence:
The hotter a thermal radiator becomes the whiter is its light.

The surface of the sun, for example, is about 6,000 K hot on average, but offers very pleasant light for the human eye since its radiation maximum is at about 500 nm.



Colour Temperatures
The hotter a black body the whiter the light emitted

As sunlight changes all the time, however (activities on sun surface, filter earth's atmosphere), it cannot be used for measurement or standard means. The sun is definitely no standard light source.

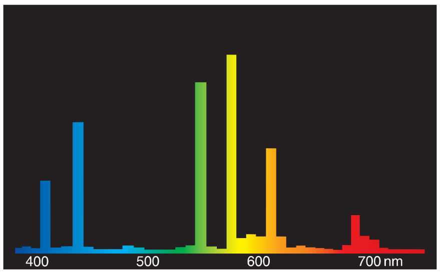
Unfortunately, a standard light source comparable to the sun cannot be made artificially, there are simply no suitable materials or stable chemical elements available.

For manufacturing filament wires for incandescent lamps tungsten is used, already, the element with the highest melting point.

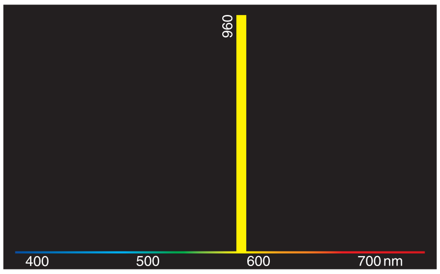
By exhaust of all possibilities – also with halogen processes etc. – in praxis incandescent lamps with colour temperatures up to 3,400 K are feasible, only.

Gas Discharge

All chemical elements can be stimulated by energy supply and release this energy again when falling back to the original state by emitting radiation. The configuration of this radiation is typical for each element, for example, mercury (Hg) emits mainly in the UV-range, other substances such as sodium (Na) yellow in the first place.

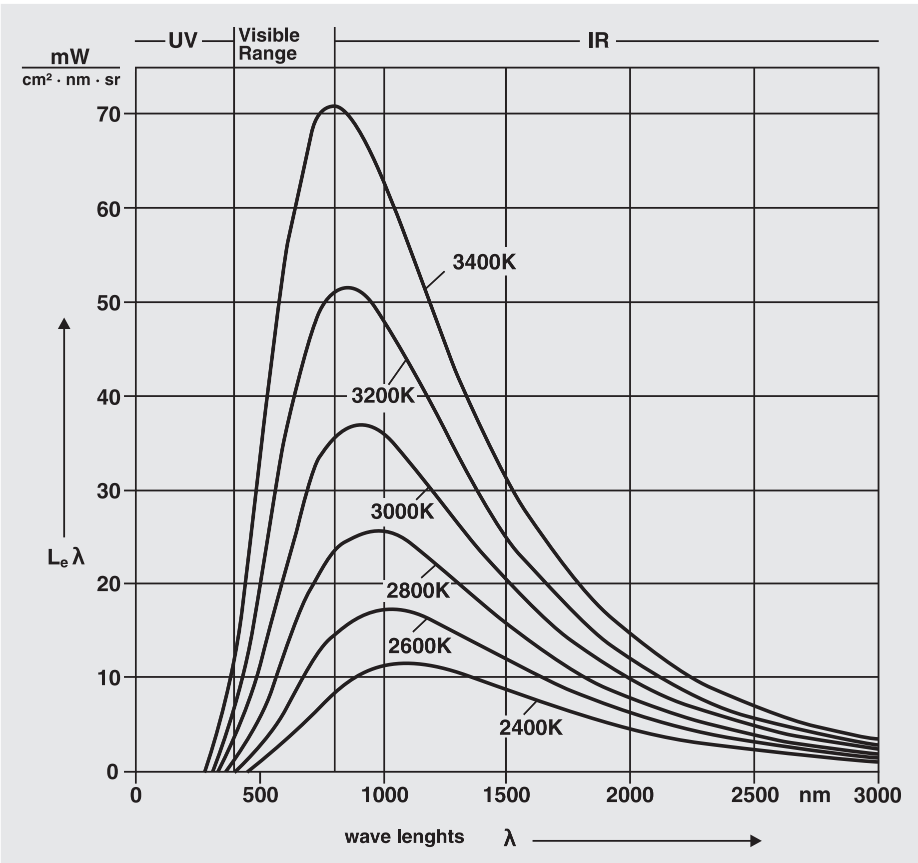


Spectrum of Mercury Vapour Lamp
Spectral radiation power distribution of mercury vapour lamps

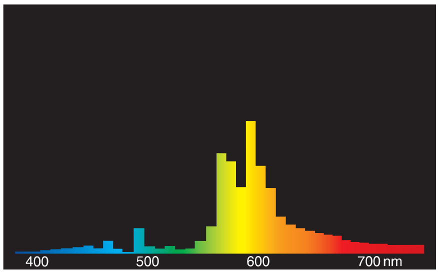


Spectrum of Sodium Vapour Low Pressure Lamp
Spectral radiation power distribution of sodium vapour low pressure lamps

The spectra of these light sources are discontinuous, they can be even monochromatic, i.e. containing only one wave length, such as sodium vapour low pressure lamps. By external circumstances the spectrum can be influenced further: for example, with sodium high pressure lamps the sodium line is widened by the pressure in the burner. Addition of mercury creates the needed blue quantities.



Isotherms of the spectral radiance distribution for tungsten as emitter
Diagram of the radiation power of tungsten material at certain temperatures (isotherms) for different wave lengths



Spectrum of Sodium Vapour High Pressure Lamp
Spectral radiation power distribution of sodium vapour high pressure lamps

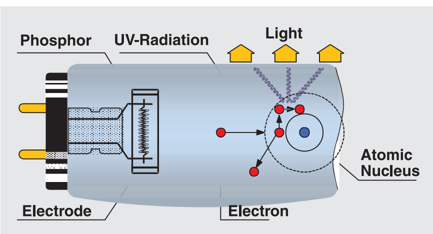
Luminescence Processes

Luminescence is a description for all processes in which a non-luminous substance or body emits radiation due to chemical reaction or activation by light.

Best known here is fluorescence: Some materials can glow even though they themselves cannot generate light. They absorb short-waved radiation (mostly UV) and transform it to more long-waved radiation (visible light).

This kind of luminescence is used in generating light essentially in fluorescent lamps. An uncoated fluorescent lamp would be a violet-blue-ish UV-radiator (due to the mercury content), the phosphor coating applied to the glass bulb from the inside changes this radiation to visible light.

The type of phosphor and its quality decide which light colour and how many spectral lines in the spectral power distribution of the light of the lamp there are in the end.



Functional Principle of the fluorescent Lamp

LASER

= Light Amplification by Stimulated Emission of Radiation

Whereas a gas discharge – for every single gas atom – is a spontaneous emission of light, is the light generating substance in a Laser triggered by an 'optical pumping process' so that high energy radiation emission emerges. The wave length of this radiation depends on the employed substance combination. Today, any colour is possible, even blue.

The generated radiation has got an extremely narrow radiation angle and can be focussed very well. This leads to very high power densities which is chance and danger at the same time: medical operations can be performed by laser beam but major damages can also be caused, naturally.

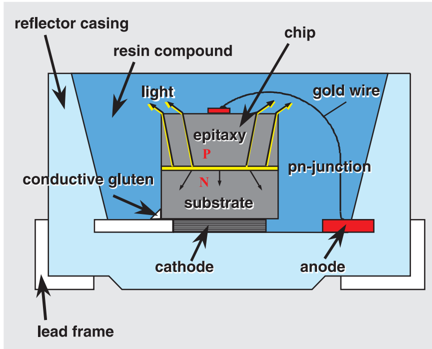
LED / OLED

Light Emitting Diode

The light of LEDs is generated by a semiconductor chip: a pn-junction is stimulated and then emits light at great intensity, quite similar to laser radiation. Therefore, LEDs were classified under the radiation protection standard EN 60–825–1 like Lasers. Due to less power, i.e. radiation power, and enough material around the light generating chip LEDs are always within the boundaries stated by the standard, hence they do not need to be included into the same danger classification.

Furthermore, as normally additional scattering optics are in employment, there is no danger for the eye. At least no more than with other lamps, either.

LEDs generate – like lasers – monochromatic light (so a certain wave length) according to the applied substance combination within the pn-junction.



Structure of a LED

In this process coloured light is generated directly and does not need to be filtered elaborately, in the first place.
White light can be created by LEDs in two different methods: via RGB colour composition of a so-called multi-LED with 3 coloured chips in one LED or by employment of phosphors in the compound around a blue chip.

In order to get reasonable values of colour rendering (Ra>70) for white LEDs with phosphors, usually yellow-orange and yellow-green phosphor are applied together.

The advantages of LEDs are clear at hand: smallest design with very little connexion powers at long service life make their employment even at difficult spots attractive. No interference by operational sounds, flickering, UV or IR radiation.

Only, unsuitable ambient conditions like humidity or high temperatures lead to failure. Now, LEDs/ OLEDs are celebrated as 'light source of the future', but experts remain in doubt. Because expenses and costs for general lighting by LED are still disproportionately high.

Organic LED

Research and development is working very hard to produce LEDs from organic materials, too: giant molecules and polymers can achieve similar qualities like the complex metal compounds in traditional LEDs.

Advantages are clear: everything stays nice and environmentally friendly and some applications are rendered possible in the first place (e.g. luminous foils via layered thin film objects).

Little displays – unichrome or multi-colour – are not a problem any more, with bigger areas there are maybe difficulties with heat dissipation and, as a consequence, power losses.

Halogen Processes

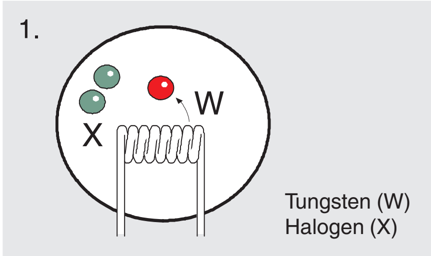
Even though the wide spread of halogen lamps suggests that halogens could be concerned with generation of light, this is not so. Halogens (group VII in the periodic table of elements – fluorine, chlorine, bromine, iodide) are supporting substances which have got an influence on light generation.

They enable material transport, e.g. tungsten atoms in incandescent lamps and filament electrodes of discharge lamps in the so-called halogen circle. In this process at sufficient temperatures (filament ≥ 2,700°C, lamp bulb ≥ 200°C) blackening is prevented and luminous efficiency enhanced.

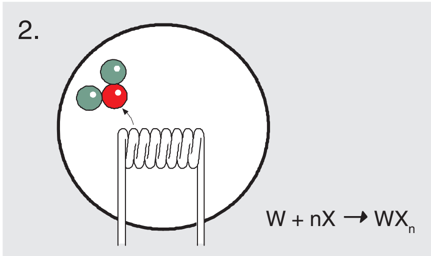
That means in detail: the atoms evaporated from tungsten filament are 'caught' by the halogen molecules near the 'cold' bulb wall at about 300°C. This complex moves around the lamp volume until it gets into the vicinity of a 'colder' part of the filament at about 2,000°C. The bonding is undone and the atom adsorbs itself to the filament.

As this 'cold' spots are to be found in the leg (ends) area of the filament usually, a certain material transport is carried out. Therefore, flaws in the tungsten wire lead to 'hot spots' where material is only carried away and the lamp's failure is pre-programmed.

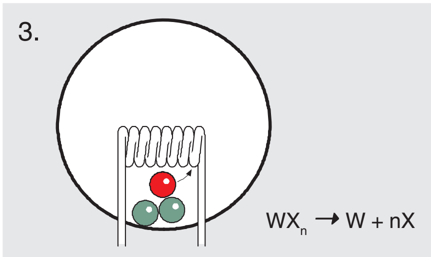
Halogen Circle



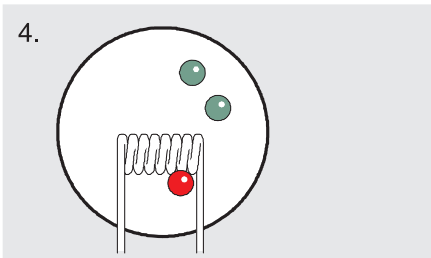
A tungsten atom disassociates from the filament



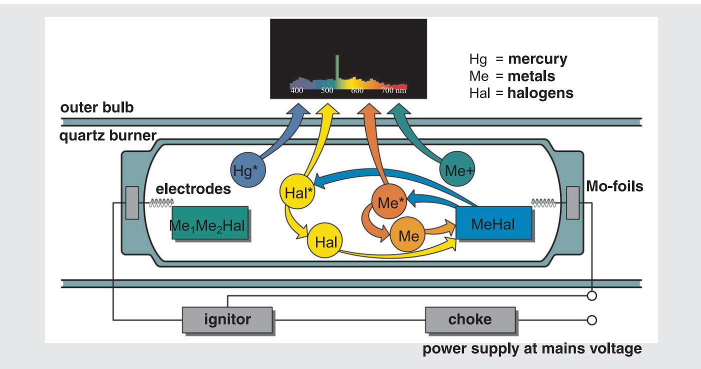
The tungsten atom is caught by the halogen gas and bound in a complex



The tungsten atom is released again to the filament by the halogen complex



Tungsten is on the filament again and the halogen gas free in the bulb volume



Functional Principle of Metal Halide Lamps

Standard Illuminants

Colour Temperatures of the Standard Illuminants

Since the colour temperature of daylight varies as well due to the position on earth as due to the course of the day (3,000 – 9,000 K / blue) it seems sensible to define certain benchmark values for standards and measurements in DIN 5031 or 5033.

As mean daylight D_{65} was characterized, for reproductive purposes (such as colour slides) D_{55} is applied, there is still D_{75} and also sometimes C can be seen (old-fashioned). For incandescent lamps' light the standard illuminant A is applicable which derives from Planck's radiator.

The colour temperature values are:

D_{65} = 6,504 K

D_{55} = 5,500 K

D_{75} = 7,500 K

C = 6,774 K

A = 2,855.6 K

Furthermore, known standard illuminants are B (sun light), G (vacuum incandescent lamps), P (petroleum and candle light) and XE (xenon lamps).

Quantities and Units in Lighting Technology

Description and Measurement of Light

Luminous Flux Φ

The evaluated radiation power (impression of brightness) of a light source altogether, i.e. in all directions, is called luminous flux. Its unit is the lumen lm.

So as to reproduce the impression of brightness accurately within the human eye the pure spectral power of a light source must be rated by the eye sensitivity curve V(λ), i.e. multiplied with it. Therefore, the photometric radiation equivalent K_m is needed which is defined for the maximum of the V(λ)-curve.

A monochromatic emitter at a wave length of 555 nm with 1W radiation power has consequently got 683 lm by definition.

Put differently:
K_m = 683 lm/W

If this calculation quantity is used for night vision rated by V'(λ) it amounts to 1699 lm/W.
For all light sources which do not emit mainly into one direction their radiation power is given in lm (see luminous intensity).

Luminous Efficiency

The luminous efficiency is a measure for the effectiveness of light sources. It shows how much light is generated by the exploited electric energy. Its unit is lumen per watt lm/W.

Quantity of Light Q

The quantity of light is a name for the rated radiation power in lmh or lms, so the radiation power in a certain period of time.

$$Q = \Phi \cdot t$$

This quantity is important for flash lights, moreover it helps with the energy assessing of planned lighting installations.

Luminous Intensity I

The radiation power of a light source into one direction in a certain solid angle Ω is called luminous intensity. Its unit is candela cd.

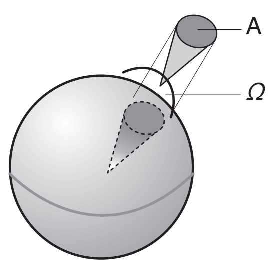
$$I = \frac{d\Phi}{d\Omega}$$

or approximately

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

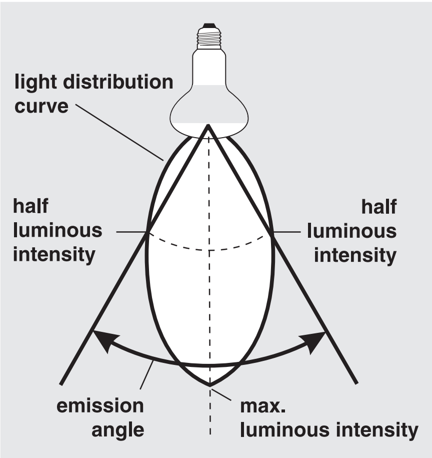
Thus, the solid angle can be imagined: a circle is cut out of the spherical surface of a ball. The cut cone down to the centre of the ball can be imagined as an 'ice-cream cornet'. The side areas of this cone enclose the solid angle, therefore, it is the 'tip of the ice-cream cornet'. Its value in Steradiant (sr) can be calculated by the quotient of the cut out surface area and the square of the ball radius:

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



Definition Solid Angle

For all light sources that emit mainly into one direction (e.g. reflector lamps) the luminous intensity in cd is quoted.
The measured radiation distribution of light sources – especially lamps in luminaires – are shown in polar diagrams, the so-called light distribution curves.



Light Distribution Curve
Example of a LDC of a reflector lamp

Illuminance E

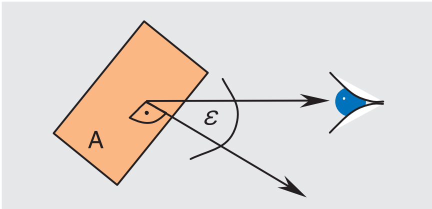
Whereas luminous flux and luminous intensity indicate the radiation power which emanates from a light source, the illuminance tells how much radiation power arrives at a certain recipient. Its unit is the lux lx.

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

Normally, this rule applies, because we can assume a sufficiently even distribution of luminous flux.

If the contemplated area is inclined towards the direction of the viewer, the tilt angle ε must be considered:

$$E = \frac{\Phi}{A} \cdot \cos \varepsilon$$



Explanation Illuminance

Therefore, it is crucial for the illuminance which area is considered in which plane. In particular for planning light installations must be kept in mind if the horizontal illuminance E_h (on tables like in offices), the vertical one E_v (e.g.on the walls of a gallery) or the cylindrical one E_z (for good, vertical sight all around) is especially important. Within the corresponding planning programs is a mean, a minimum and a maximum illuminance calculated, respectively, in order to get an impression of the uniformity of lighting.

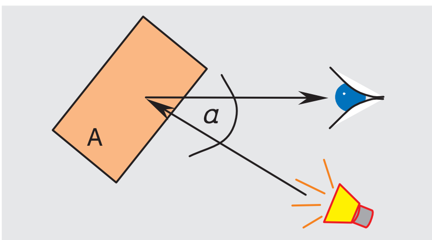
Examples of values of illuminances:

Summer day	60,000 – 100,000 lx
Hazy winter's day	3,000 lx
Desk place in office	500 lx
Full moon night	0.25 lx
New moon night	0.01 lx

Luminance L

The impression of brightness given by a certain area is called luminance. Its unit is cd/m² or cd/cm².

$$L = \frac{I}{A}$$



Explanation Luminance

If the contemplated area is not observed vertically, the deviation angle α must be considered:

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

The higher the luminance of an object, e.g. of a lamp, the brighter it appears and it can rather cause glare.

Photometric Law of Distance

The further off an object is from the light source the weaker its illuminance becomes. Or put more exact: Its illuminance decreases with the square distance.

$$E = \frac{I}{r^2} \cdot \cos \alpha$$

Light Exposure H

In photography everything depends on the all-over amount of light which reaches the light sensitive area – the film – within a certain period of time.

$$H = E \cdot t = \frac{Q}{A}$$

Light and Emotion

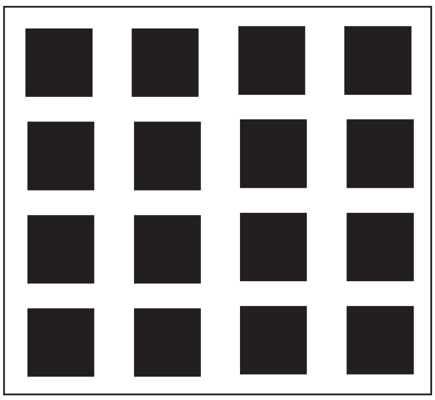
We need light for eye vision. But there is also a strong connection to emotion and well-being: light colours and lighting situations have got a lot of influence on our feelings, mostly more subjective and individual than can be measured or proven as a matter of fact.

Therefore, accepted findings usually derive from very elaborate statistical studies.

Warm colours (warm white, incandescent lamps' light) are considered un-comfortable by most people when illuminance excedes 2,000lx and not only due to the high heat load.

Cold colours (daylight, coolwhite) are experienced quite unpleasant at illuminances under 1,000lx. Therefore, indoors the colour temperature of the light should be chosen under 5,500 K or high illuminances greater than 1,000lx should be planned right from the start.

In fact, the sensation of brightness always depends on the luminance, but it cannot be measured exactly by the human eye. That means, all the time the eye compares between the existing points and areas and tries to find a specific balance even if there are strong contrasts.



Optic Illusion
Optic illusion: at the white crossing points the eye 'sees' dark spots

Light Effects on a Human Being

Biological Effects

Light controls our activity and has got its influence on our whole life. Especially the skin as an area organ is exposed to the whole radiation with UV and IR. As well, UV radiation is needed for triggering certain processes within the body like generation of vitamin D_3. Too high doses, however, can cause considerable damages. Sun burn or conjuncitivitis are just a few examples of those injuries.

The human being as day active creature is more energetic and makes less mistakes with higher illuminance, even if the task itself is not depending on the visual ability. This higher action is even measurable, for example at the composition of the blood, there are more white blood cells in it.

All in all, concentration is much higher, therefore, there are much less accidents to be expected. Consequently, especially in occupational safety and road traffic good lighting must be observed.

Light Needs

Every human person has got individual needs as regards illumination. So, it is statistically proven that at good lighting (about 1,000lx) older people work approximately as well as young ones. When lighting is bad the older ones make definitely more mistakes. Moreover, it is sensible to plan light controlling installations so that the user can have the possibility of exerting manual influence.

Disturbance due to Light

Light and light sources cannot just be help for eye vision, but also can bother significantly, for example as light immission or by glare.

Moreover, higher heat load can arise especially due to incandescent lamps which has to be carried away with elaborate air conditioning technology.

Light immissions – meaning brightness unasked for in the dark hours, e.g. indoors due to street lighting – are just annoying most of the times, sensitive people can be disturbed by that to a great intent. Relief can be brought quite easily by suitable methods:

- Darken highly illuminated buildings at night
- Keep lighting constant and even, no use of dynamic light like banners or animated coloured pictures
- Change positions of luminaires
- Change kind of luminaire: height, inclination, light distribution

Glare, on the other hand, is a big problem, not just uncomfortable but also preventing people from achieving.
Scattered light, shine, mirror effects – i.e. reflexion in one direction – can lead to a very strong light beam into the eye locally so that it must see against the light almost. In road traffic or at dangerous tasks at work glare can be a great safety risk, therefore. Normally, it is 'just' very strenous and tiring. Then, quick tiring and eye problems are the consequences.

The more diffuse light is reflected (for example, off a white wall), the less it is conceived as glare. Further disturbances can emerge from hard shadows at high illuminances, for example, or from frequency problems with discharge lamps when there are stroboscopic effects arising from them.

No human being has to accept bad lighting, there is always a possibility to change at least something. Professional and independent light planning, good lamps and luminaires guarantee a comforting atmosphere.