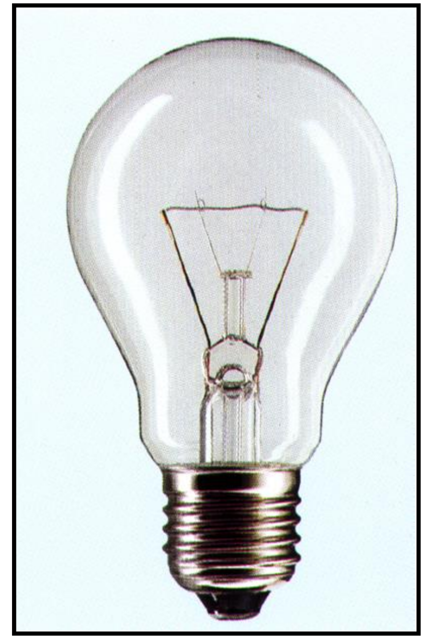
4. Incandescent and Halogen Lamps

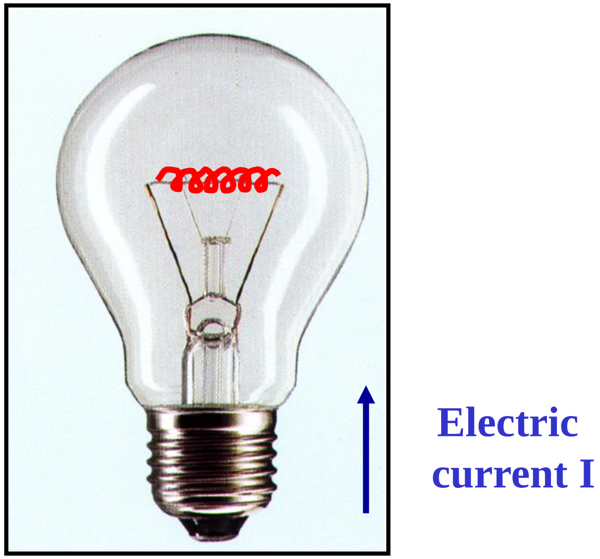
Contents



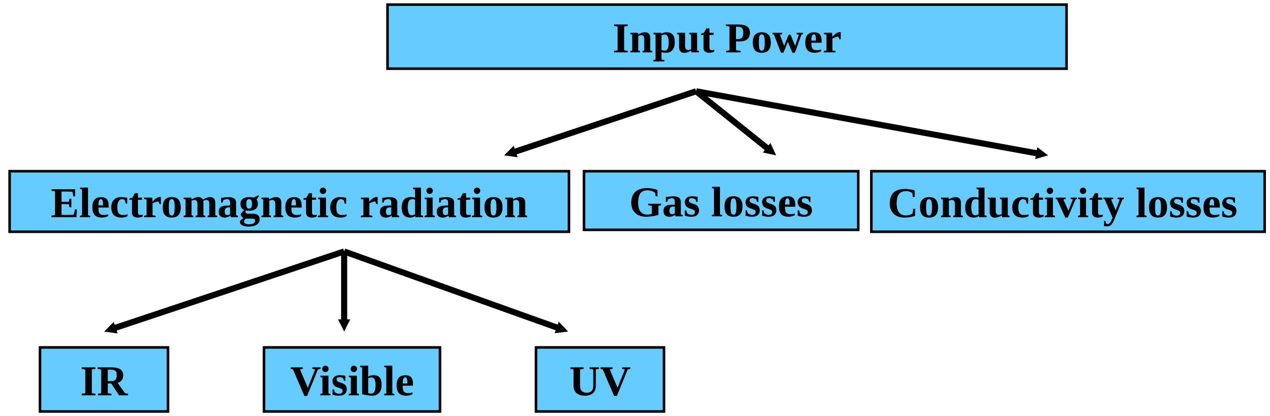
4.1 History

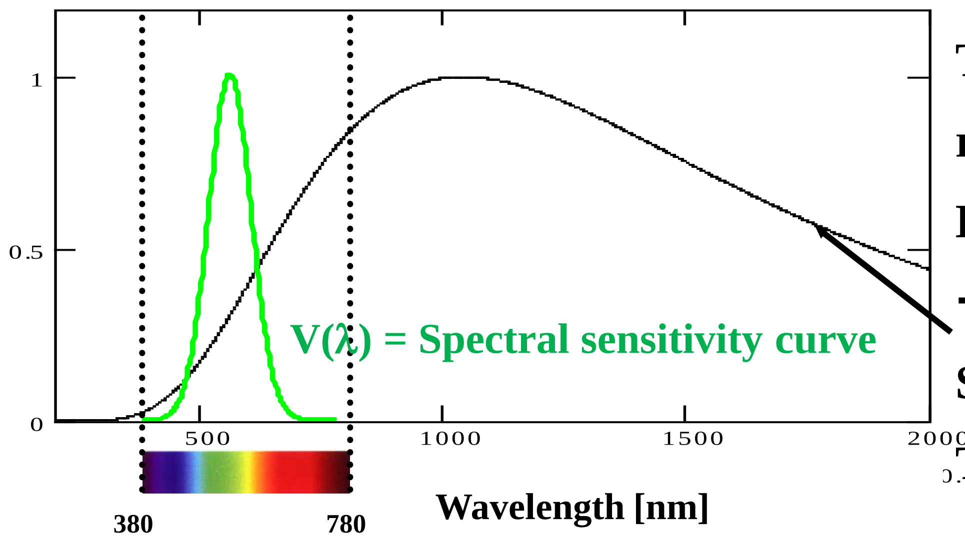
1820	Arthur de la Rive observes a glowing Pt-wire in vacuum
1840	Joseph Wilson Swan experiments with carbonised paper wires
1854	Heinrich Goebel constructs the first incandescent lamp with a bamboo fiber, which finally leads to the carbon filament lamp Problem: still not sufficiently well evacuated $\Rightarrow$ $C + O_2 \rightarrow CO_2$
1868	First fabrication of incandescent lamps by Swan (low lifetime)
1879	Patent of Thomas Alva Edison Edison improves incandescent lamps by better evacuation of the lamp bulb $\rightarrow$ higher lifetime
1881	Demonstration (Presentation) of Edison Lamp at the World Exhibition in Paris Coil still made from C Searching for high melting metals $\rightarrow$ Ta, W, Re, Os Winner: Tungsten because of the lowest vapour pressure $\Rightarrow$ lowest blackening
1900	Max Planck: Theoretical basis (Planck's law)
1902	Osmium wire (Auer and Welsbach)
1911	Ar/N_2 filling
1912	Tungsten wire
1936	First lamp with a double coiled filament
1958	First application of Xenon as a filling gas
1960	Halogen cycle (Zubler and Mosby, GE)
1971	First H4 automotive lamp (today also H7)
1973	First halogen lamp with interference filter
2010	Incandescent lamps marketed as heat balls due to ban of stand. incandescent lamps

4.2 Physical Fundamentals



Energy balance of an incandescent lamp





Tungsten filament with the electrical resistance R

Electric loss for current I

→ $P = U*I = R*I^2$

Spectrum of a glowing filament at about T = 2700 K (incandescence)

4.2 Physical Fundamentals

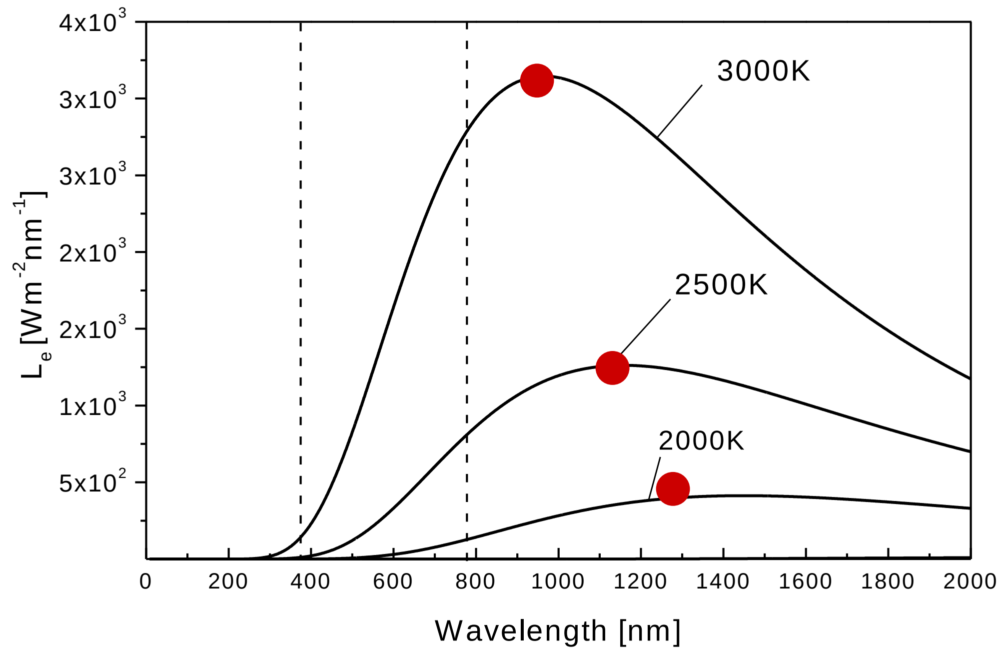
The black body radiation can be defined as the light emission in thermal equilibrium (thermal radiation)

Planck's radiation law (1900)

$$L_e = \frac{c_1}{\lambda^5} \cdot \frac{1}{e^{c_2/\lambda T} - 1}$$

c_1 = $2\pi hc^2$ = $3.741832 \cdot 10^{-16}$ Wm^2
c_2 = hc/k_B = $1.438786 \cdot 10^{-2}$ Km
λ = Wavelength [m]
L_e = Spectral irradiance (radiation density)
T = Temperature [K]

Spectrum of a black body radiator



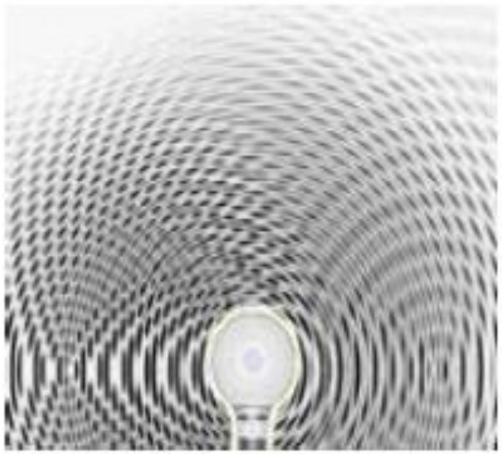
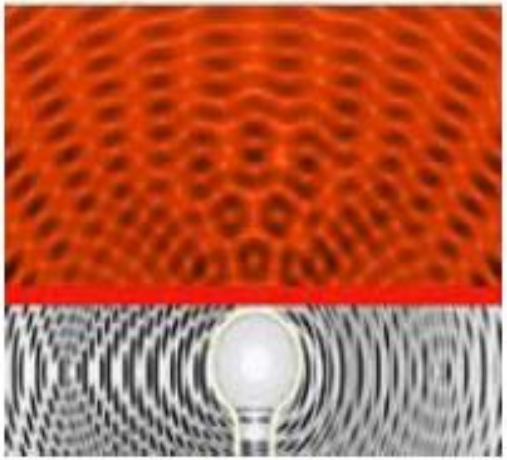
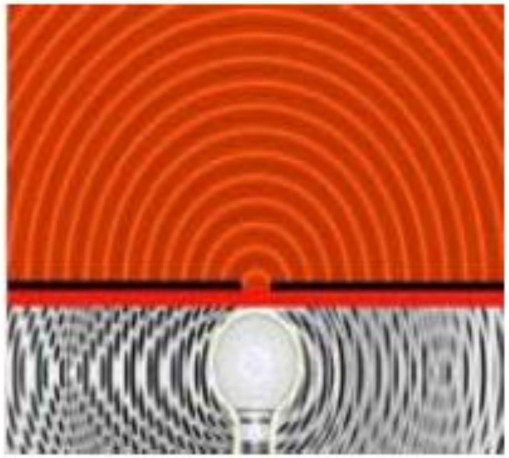
Light source	Color temperature
Sun	5800 K
Studio halogen lamp	3400 K
Halogen lamp	3000 K
Incandescent lamp (bulb)	2700 K

Wien's displacement law

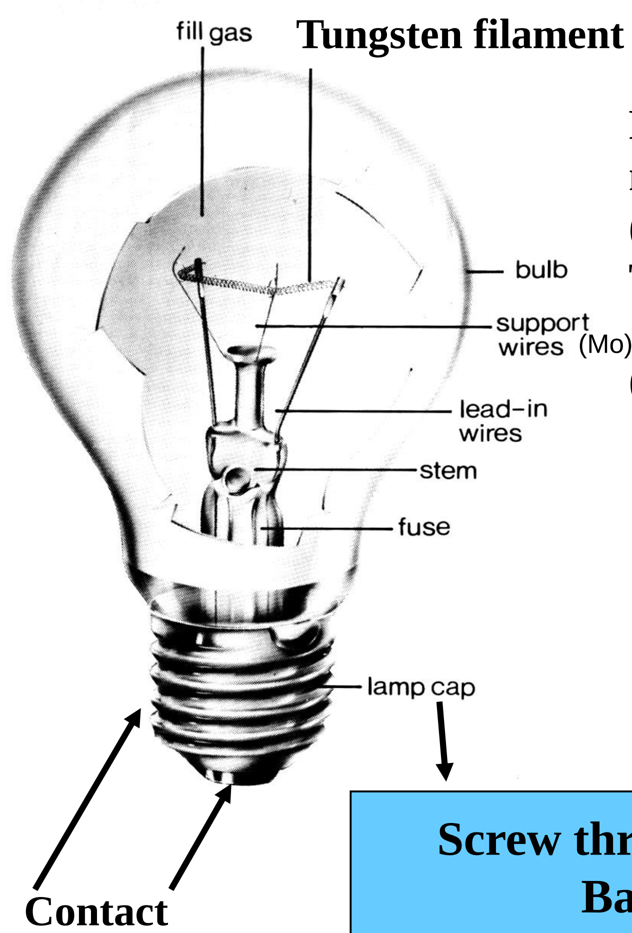
$$\lambda_{max} \cdot T = 2880\,[\mu m \cdot K]$$

4.2 Physical Fundamentals

Incandescent and halogen lamps are spatially and temporally incoherent light sources

Incoherence	Temporally coherence	Spatially and temporally coherence
		
A light bulb radiates incoherent: the wavelengths of the individual waves are different or between the various points of the radiating surface, there is no fixed phase relationship	A color filter allows only light of a certain wavelength to pass through: the radiation is temporally coherent (monochromatic)	Through color filter and pinhole a small-area, temporally and spatially coherent light source of very low intensity is created

4.3 Construction



Fill gas =
noble gas (Ar, Kr, Xe) + N_2
(pressure = 1 bar)
Typical: 80% N_2 + 20% Ar

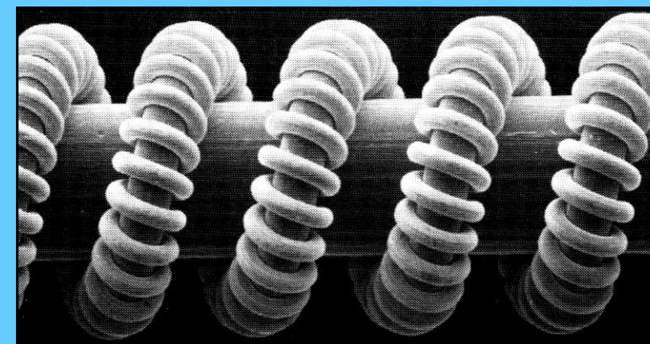
(N_2 is rather inert)

Ar	39.9 g/mol
Kr	83.8 g/mol
Xe	131.3 g/mol

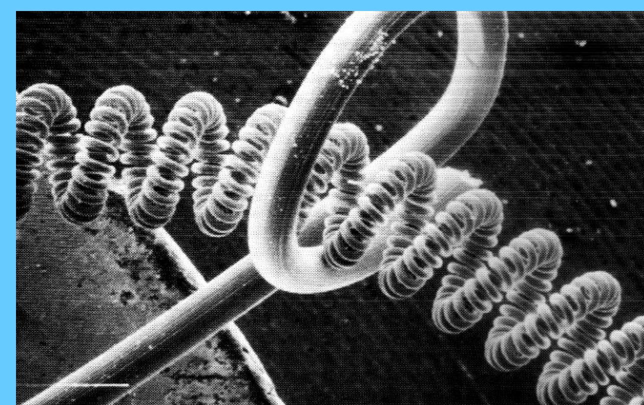
Screw thread = Edison-Type
Bajonett-Type
Diameter in mm

Europe	E10	E14	E27	E40
USA	E12	E17	E26	E39

Filament is double coiled

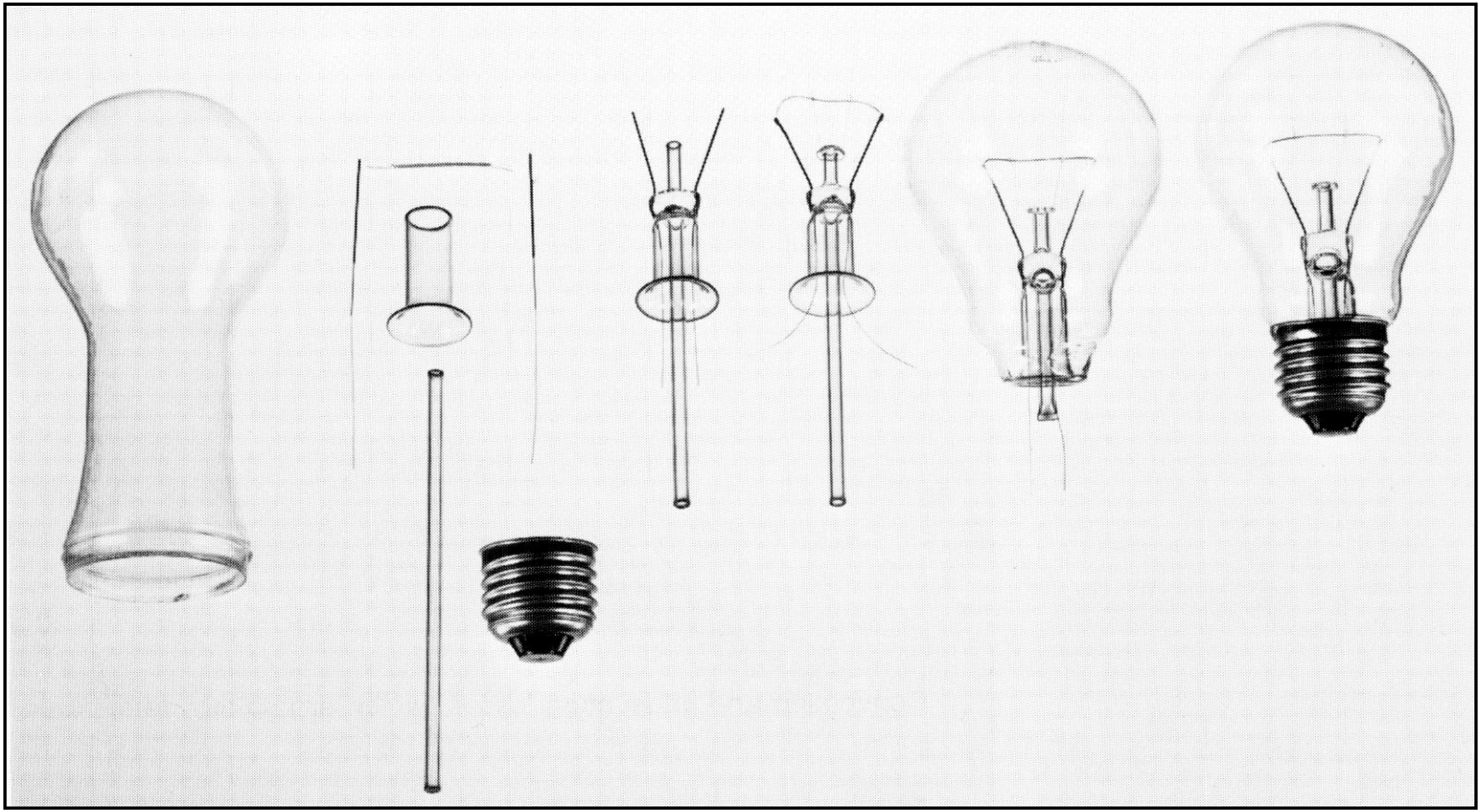


It is coiled initially on Mo, then Mo is removed



4.3 Construction

From a glass bulb to an incandescent lamp



4.3 Construction

Production of tungsten filament (Mohs hardness 7.5)

Tungsten production

Ores: $CaWO_4$ or $(Fe,Mn)WO_4$
"Scheelite" "Wolframite"

↓ Digestion with HCl

$MeCl_2 + WO_3 \cdot H_2O$ "Tungstite"

↓ Leaching with NH_3

$(NH_4)_{10}[H_2W_{12}O_{42}]$ "Paratungstate"

↓ 600 °C

WO_3

↓ Doping, H_2, 450 °C

α-W-metal powder → Pressing + sintering to W-staves

Filament production

W-staves

↓ Hammering, rolling

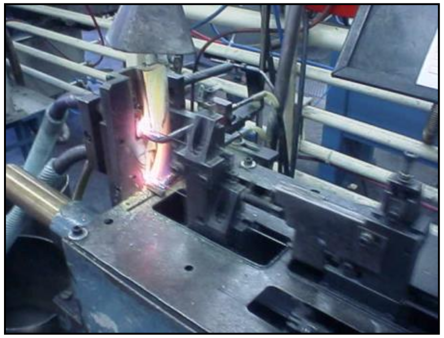
W-plates

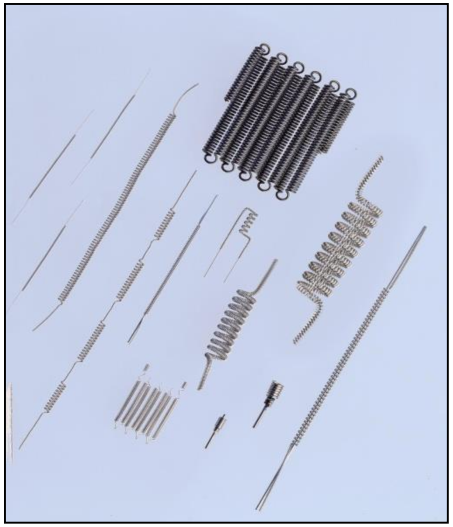
↓ Pulling

W-wires

↓ Winding/coiling

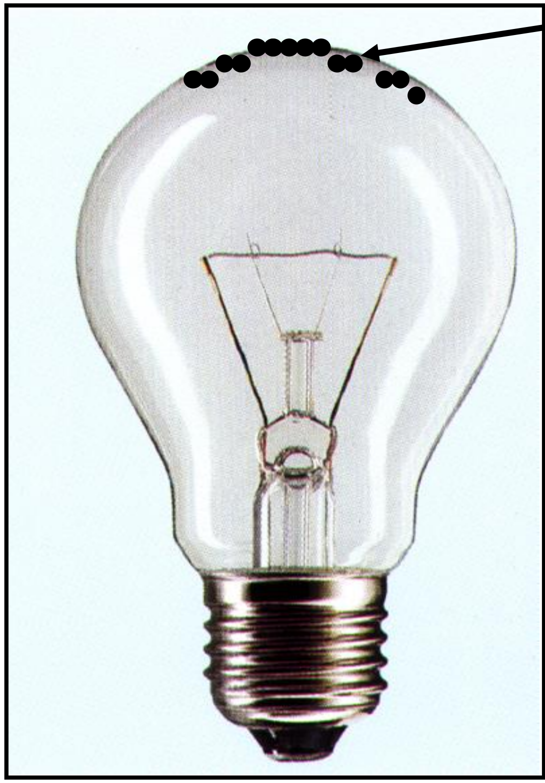
W-filament



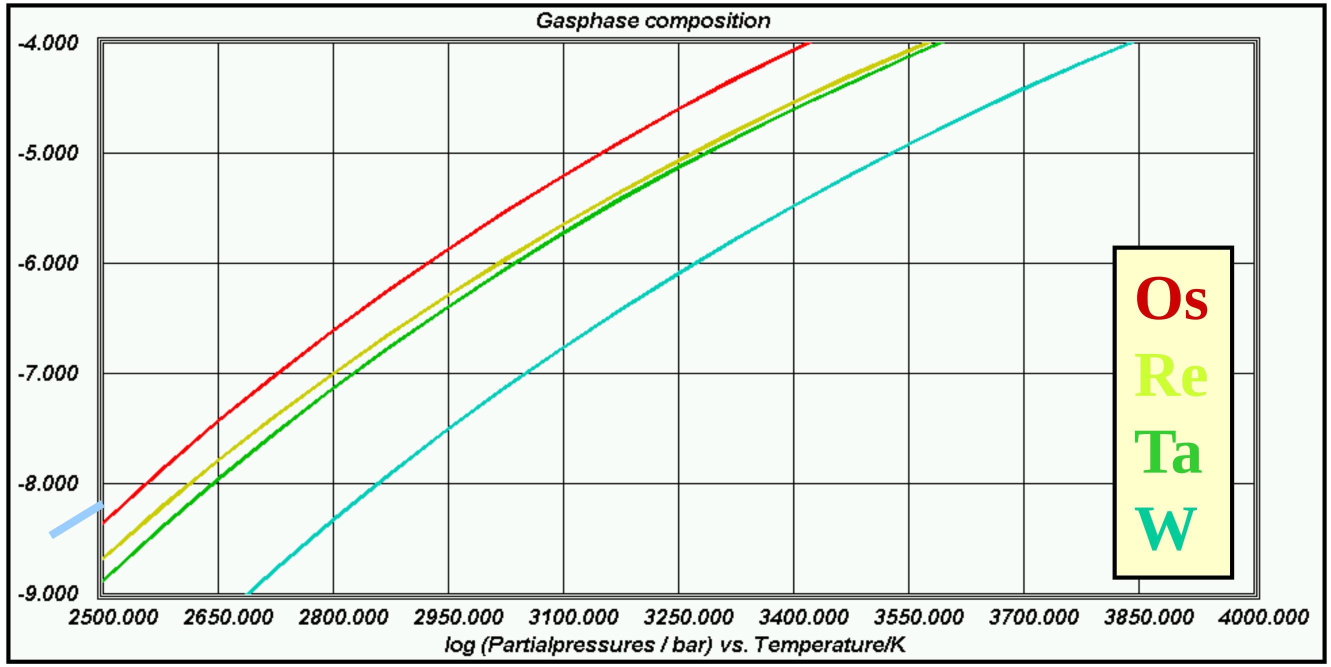


4.4 Lifetime

Blackening of incandescent lamps



Tungsten which evaporates from the filament condenses inside of the glass bulb



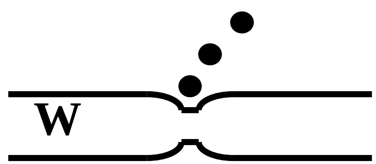
Tungsten has the lowest vapor pressure and the highest melting point of all metals (Tm = 3410 °C), Carbon (graphite) melts at 3550 °C

4.4 Lifetime

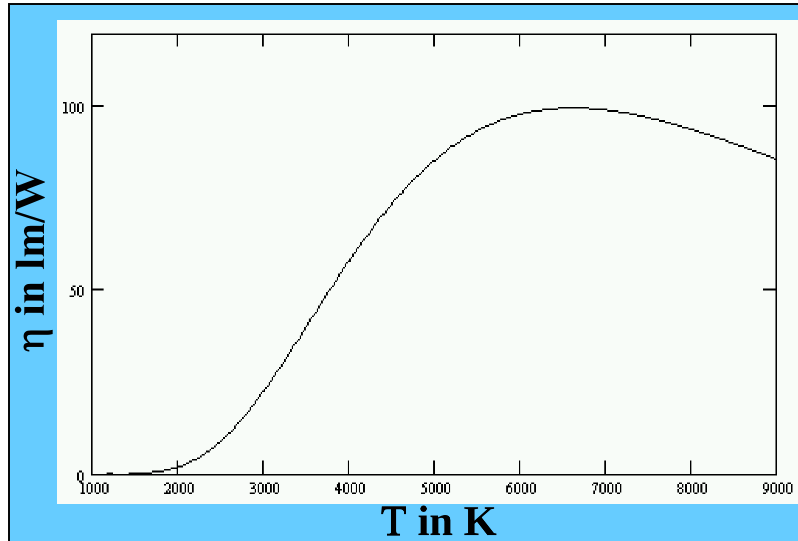
The hotter is the filament, the more efficient is an incandescent lamp, however blackening is then also stronger

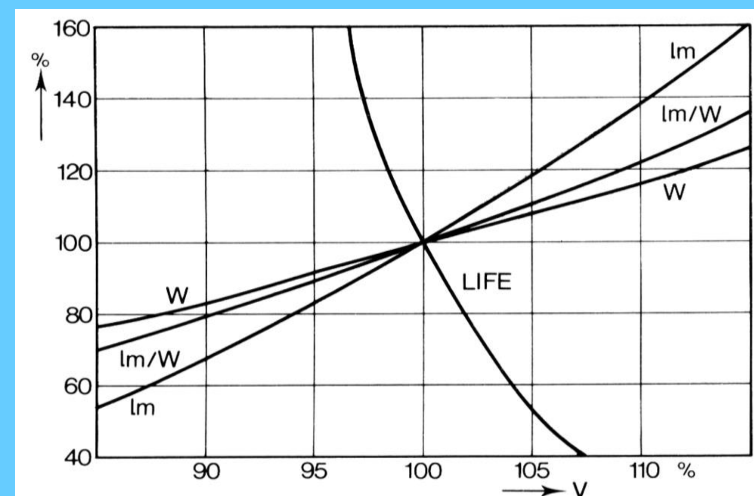
Operating conditions of an incandescent lamp represent a compromise between the energy efficiency η and lifetime t.

Typical values for operation at nominal voltage:
η = 13 lm/W and t = 1000 h



<u>„Hot spot“- mechanism</u>
W-wire becomes thinner
⇒ Resistance increases
⇒ Local output and temperature increase
⇒ Vapour pressure increases
⇒ Burning-out at „hot spot“

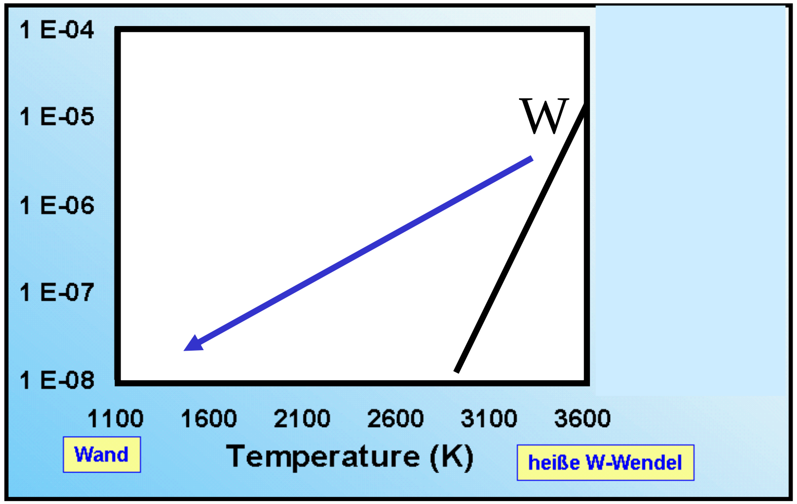




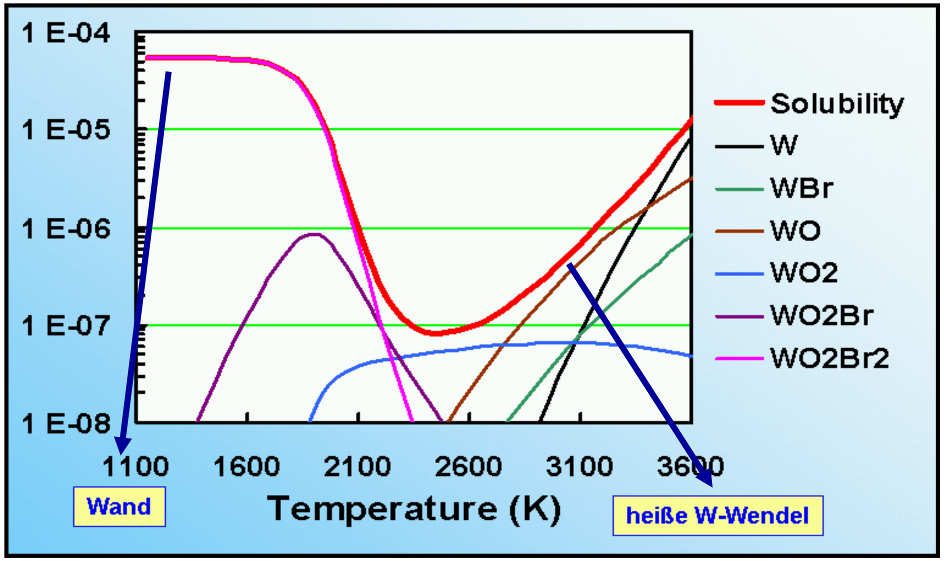
4.5 Halogen Incandescent Lamp

Functional principle

In halogen incandescent lamp tungsten is transported back to the filament from glass bulb via chemical transport ⇒ Glass bulb remains clear



Filling gas = nobel gas + O_2 + X_2 (X = Br, I)



= Solubility curve

$= p_W + p_{WO} + p_{WBr} + \ldots$..

(p = partial pressure)

4.5 Halogen Incandescent Lamp

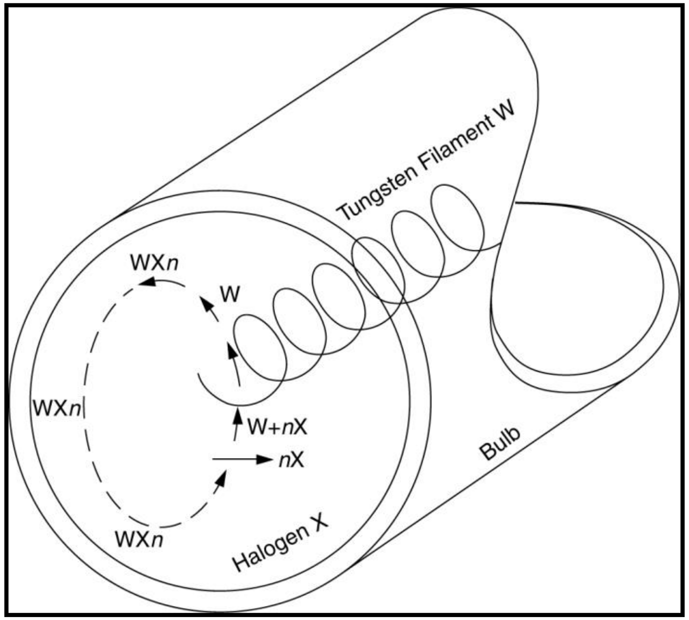
Chemical transport in halogen incandescent lamps (X = Br, I)

The position of the chemical equilibrium is temperature dependent: W + O_2 + $X_2 \rightleftharpoons WO_2X_2$

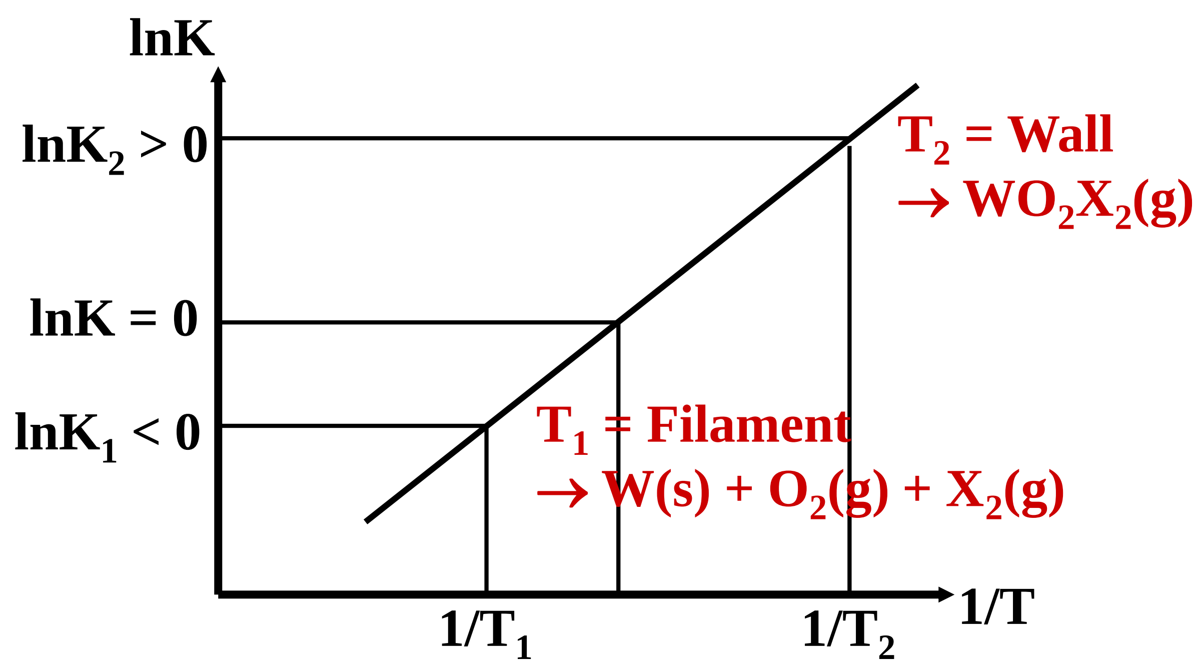
$$\ln K = -\frac{\Delta H^0}{R \cdot T} + \frac{\Delta S^0}{R}$$

van‘t Hoff eq.

Halogen cycle



$W + O_2 + X_2 \rightleftharpoons WO_2X_2$ Chemical transport



4.5 Halogen Incandescent Lamp

Limitation of the W-Recycling

- **Although W back transport is efficient, no curing of the W-filament occurs**
- **Gaseous W condenses at the cold spot (thickest section due to lowest resistance)**

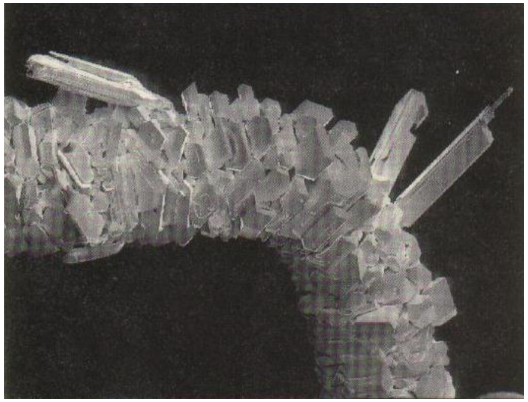
$$W + \frac{1}{2} O_2 \rightleftharpoons WO$$

$$WO + \frac{1}{2} O_2 \rightleftharpoons WO_2$$

$$WO_2 + \frac{1}{2} O_2 \rightleftharpoons WO_3$$

$$2\,W_{(s)} + 3\,O_{2(g)} \rightleftharpoons 2\,WO_{3(s)} \quad \Delta H^0 = -764\ kJ/mol$$

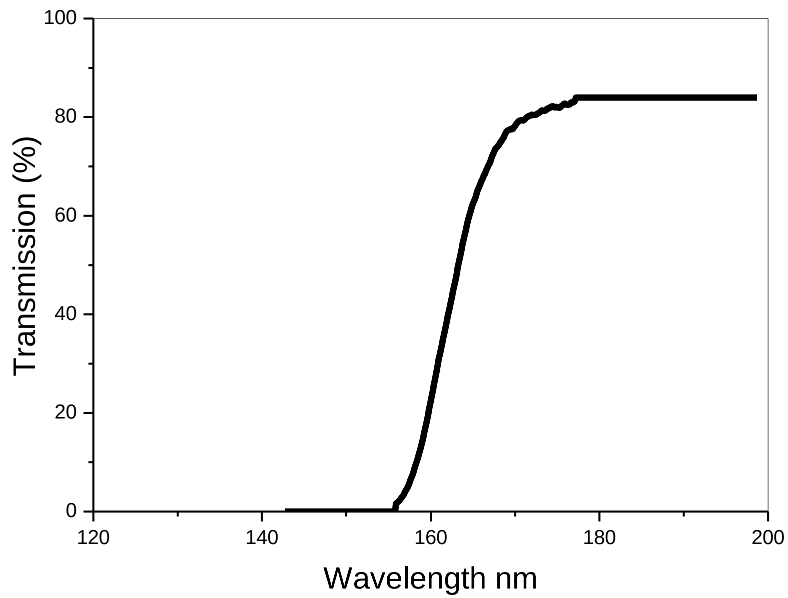
Tungsten crystals



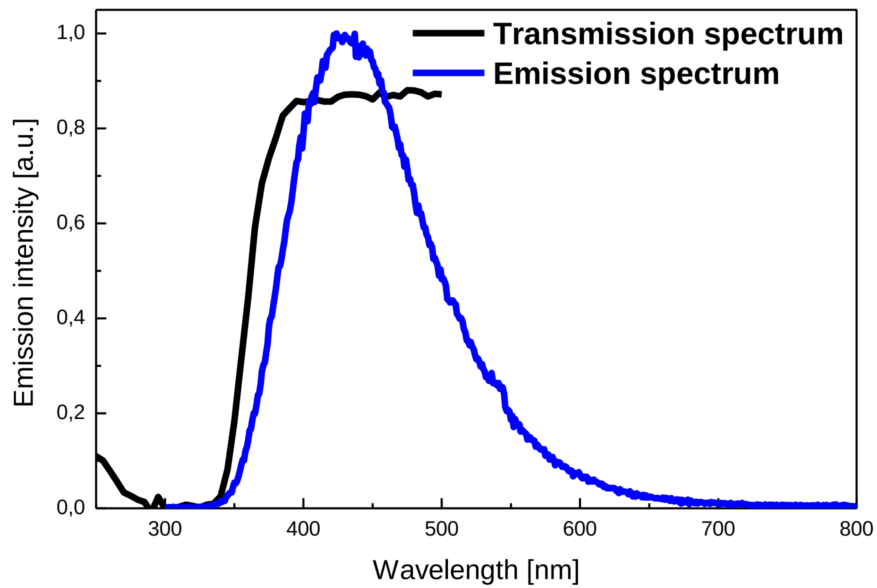
Set of problems with UV radiation

Due to the higher filament's temperature, halogen incandescent lamps emit also some of UV-A and UV-B radiation, since the quartz bulb is transparent to UV radiation.

Transmission spectrum of quartz glass



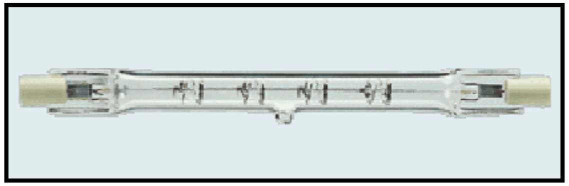
Transmission and emission spectrum of Ce^{3+} doped silica glass



4.5 Halogen Incandescent Lamp

Advantages over incandescent lamps

In halogen incandescent lamp remains the (bulb) wall, during the chemical transport, clear
⇒ Reduction of bulb size
⇒ Increase the noble gas pressure
⇒ Lower evaporation rate of tungsten gives a higher lifetime, what gives partly higher efficiency (higher filament temperature)

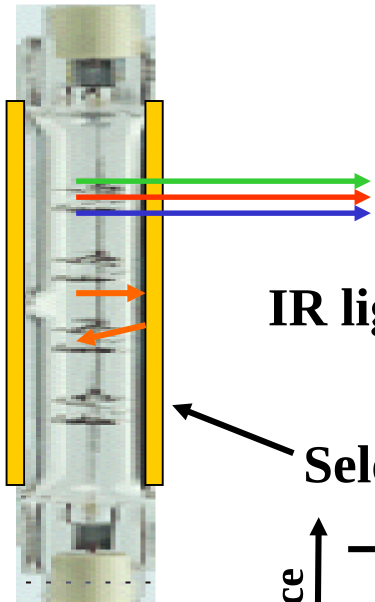


T [K]	η [lm/W]	η [%]	
2700	13	10	Incandescent lamp
2800	16	11	
3000	22	13	Typical halogen lamp
3200	29	16	Special halogen lamp (Projectors, TV-studios)
3400	36	20	

4.6 Interference Filter

Since incandescent lamps and halogen incandescent lamps emit substantially IR-radiation, even higher efficiencies can be achieved by IR filter

Principle on the example of the halogen lamp

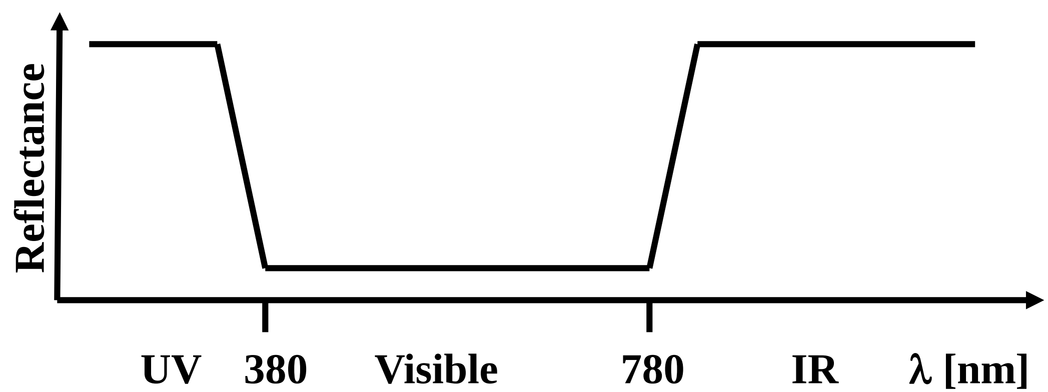


Visible light is transmitted

IR light is reflected back to the filament

$\eta = 20\ \text{lm/W} \Rightarrow 40\ \text{lm/W}$

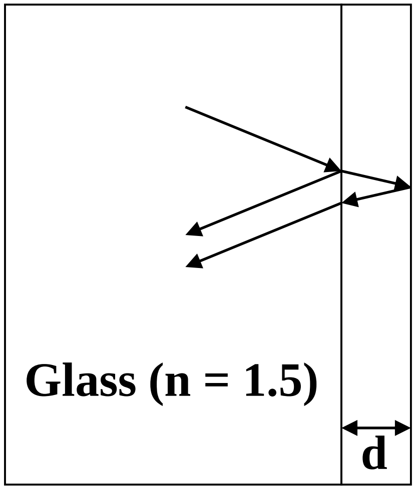
Selective mirror



→ Interference filter

4.6 Interference Filter

Interference filters consist of a sequence of low-and highly refractive inorganic layers



Path difference = 2nd - λ/2

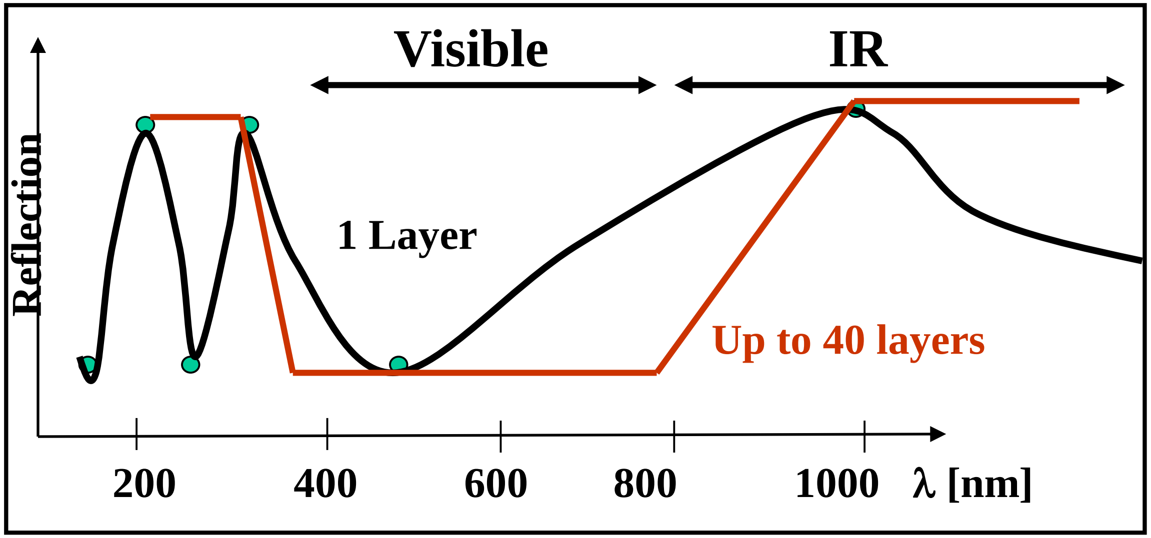
- m·λ → Constructive interference, High reflectance
- (k+1/2)λ → Destructive interference, Low reflectance

TiO_2, ZnS, ... (n = 2.3 – 2.7)

Example: 2nd = 500 nm

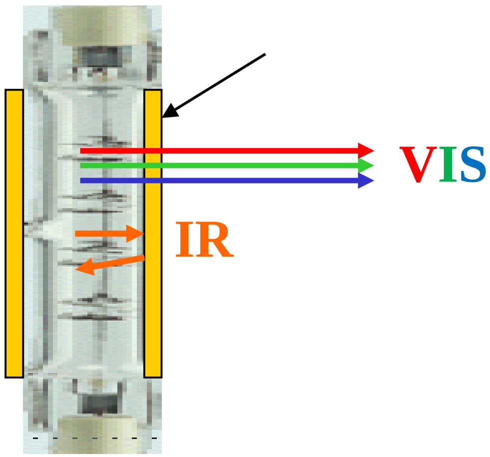
Low reflectance
- k=0 λ = 500 nm
- k=1 λ = 500/2 = 250 nm
- k=2 λ = 500/3 = 167 nm
- ......

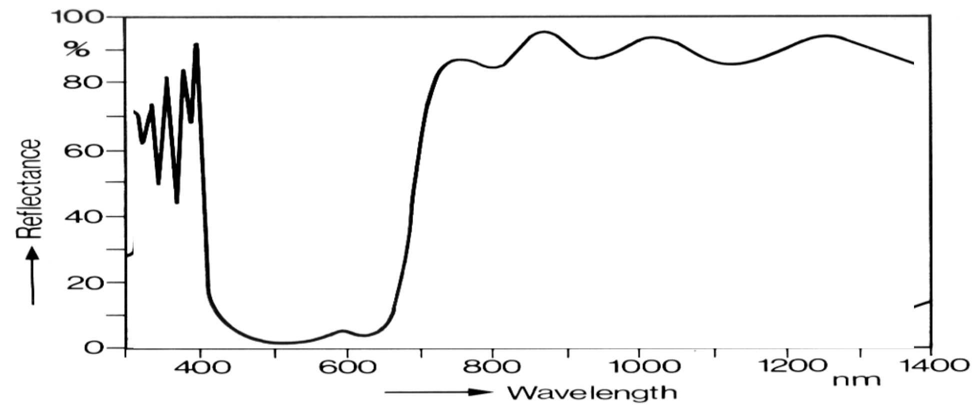
High reflectance
- m=0 λ = 500/0.5 = 1000 nm
- m=1 λ = 500/1.5 = 333 nm
- m=2 λ = 500/2.5 = 200 nm
- ......



4.6 Interference Filter

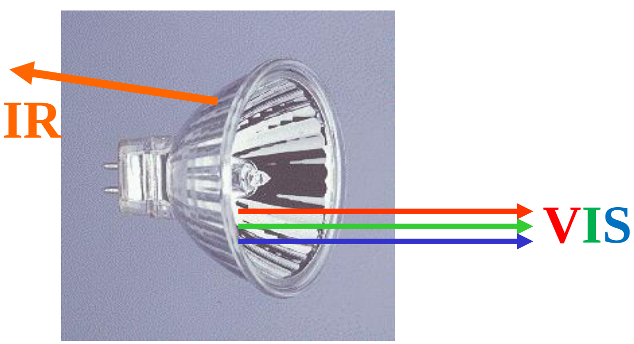
Energy saving filter

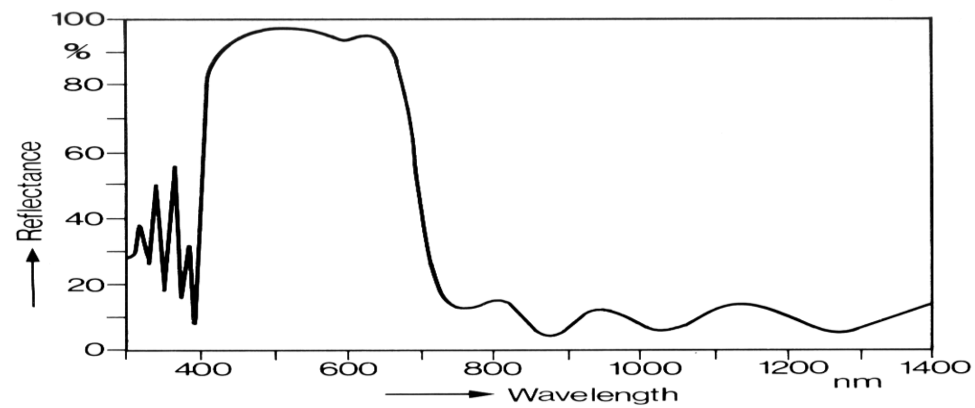




Cold light mirror

Cold light mirror is an inverse energy saving filter:
It reflects visible light and let IR radiation pass through.



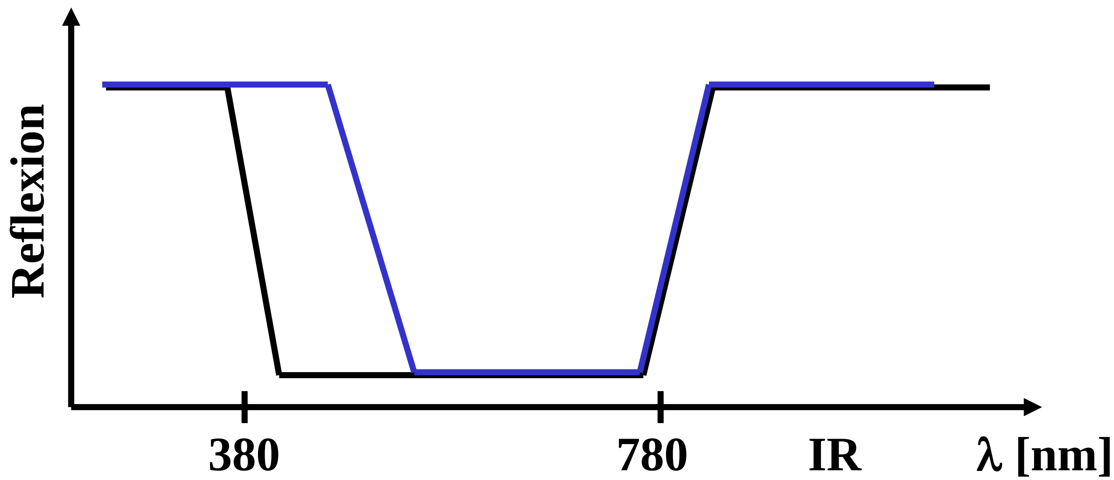


Cold light reflector are not perfect, i.e. deep red and deep blue are visible behind the lamp

4.6 Interference Filter

Interference filter as colour filter

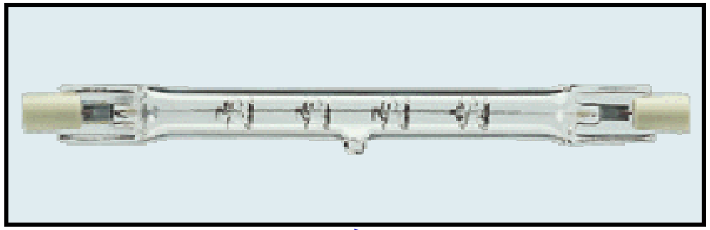
Application in light sources and spectrometers



Lack of blue in emission spectrum ⇒ yellow filter

4.7 Types of Halogen Lamps

Halogen lamps for general lighting



P = 200 - 500 W
U = 230 V
$P = U^2/R$, i. e. U↑ ⇒ R↑ required
⇒ $R = \rho * l/A$
⇒ Longer and thinner filament
⇒ Filament is less stable
⇒ $T_{filament}$ is lowered
⇒ η decreases in comparison with low voltage lamps

Low-voltage halogen lamps

U = 12, 24 V (Transformator is required)
P = 20 - 50 W

High-voltage halogen lamps

Outer envelope (hot & fingerprints)

PAR = Parabolic reflector lamp

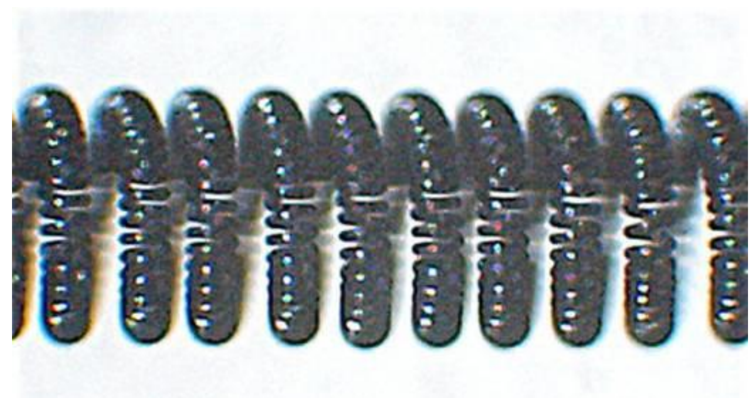
4.7 Types of Halogen Lamps

Low Voltage vs. High Voltage Halogen Lamps

Lamp type	Low voltage	High voltage
Voltage U [V]	12	230
Power P [W]	20	20
Filament length l [cm]	2.21	15.81
Diameter d [µm]	54.1	7.558

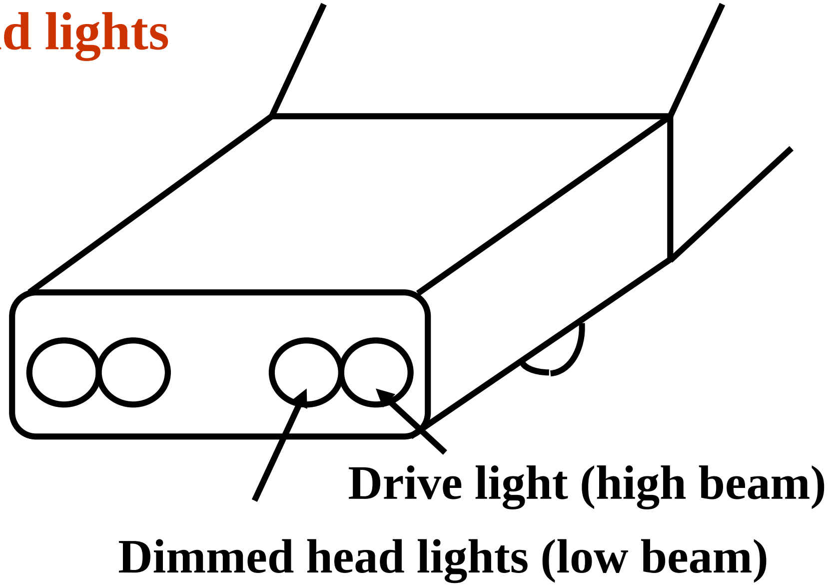
$$l = \sqrt[3]{\frac{P\ U^2}{4\ \pi \rho \sigma^2\ T^8}}$$

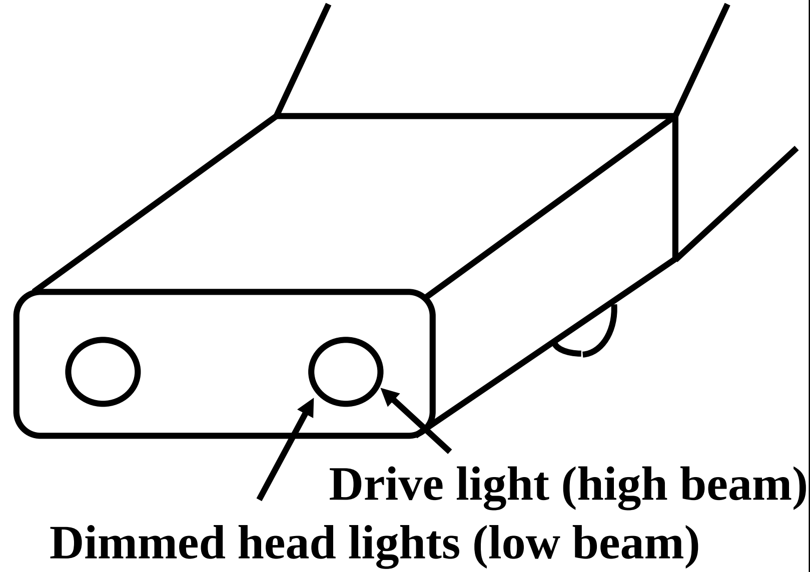
$$d = \sqrt[3]{\frac{P^2\ \rho\ 4}{\sigma\ \pi^2\ T^4\ U^2}}$$



4.7 Types of Halogen Lamps

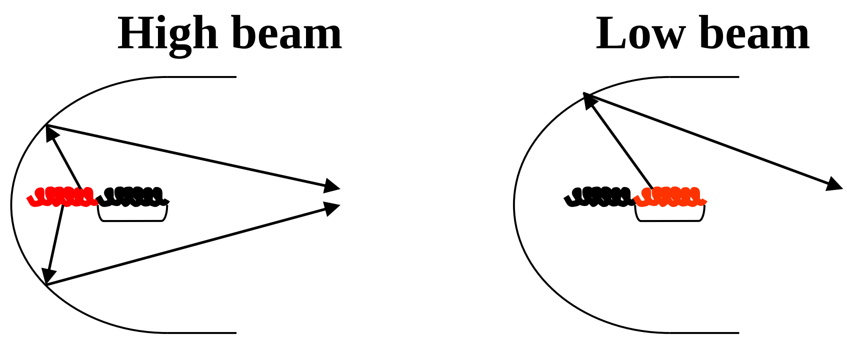
Car head lights





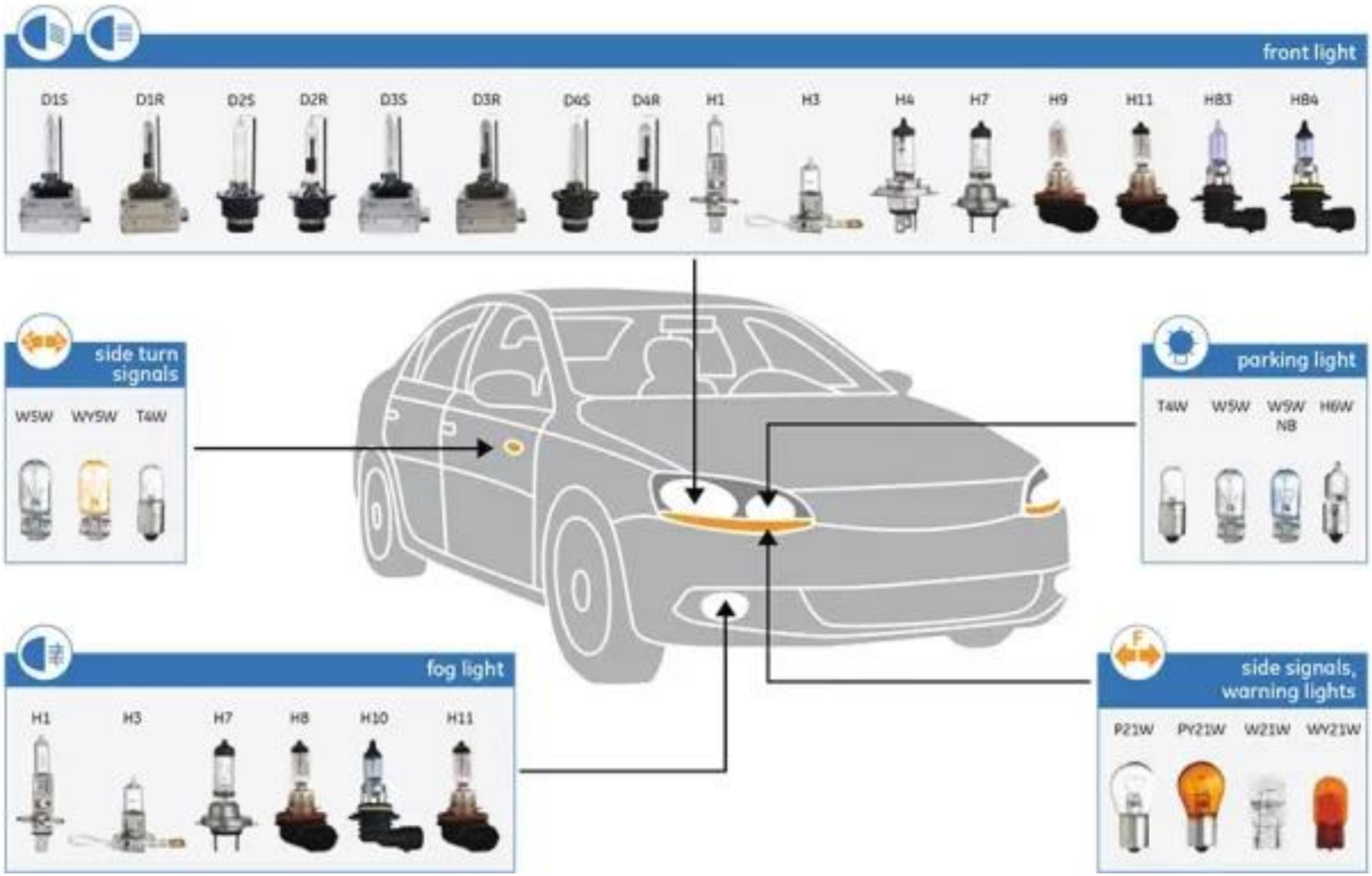
H7-Lamps
(1 Filament)

H4-Lamps
(2 Filaments)



4.7 Types of Halogen Lamps

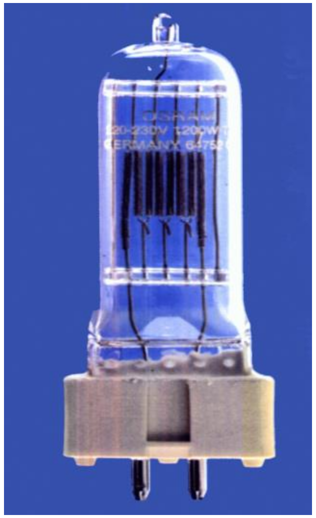
Automotive bulb types



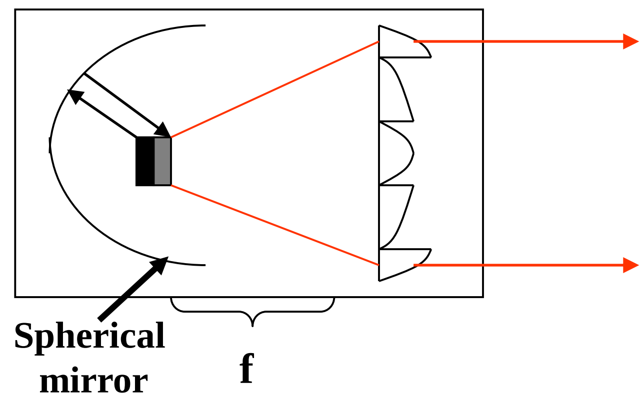
Source: https://gomechanic.in/blog/headlight-sockets-explained/

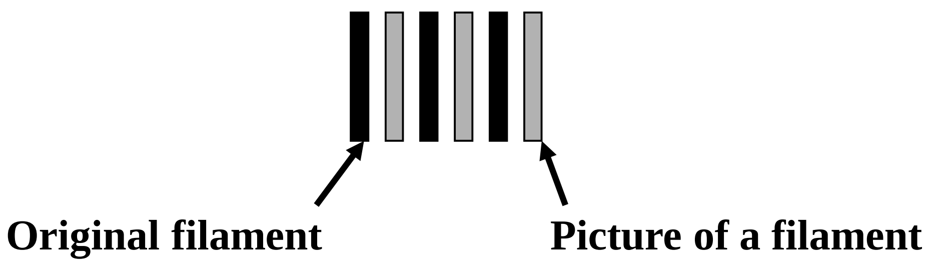
4.7 Types of Halogen Lamps

Halogen lamps SSTV Market (Stage-Studio-TV)

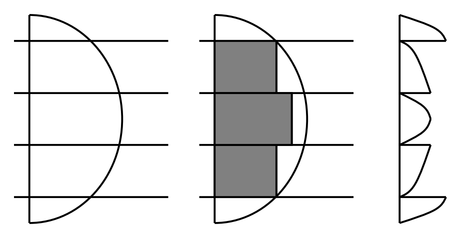


Headlamp





Fresnel lens



4.8 New Developments

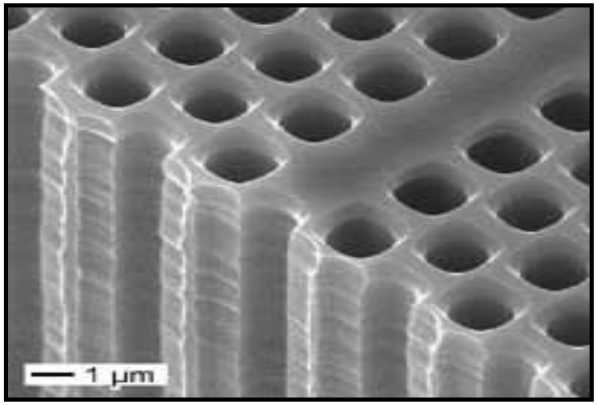
White LEDs are becoming strong competition for halogen incandescent lamp

Light source	Luminous flux [lm]	Efficiency [lm/W]	Brightness [Mcd/m²]	CRI	Lifetime [kh]	Costs [$/Mlm·h]
Incandescent 60 W	900	15	10	100	1	7.2
Halogen 50 W	1000	20	20	100	2	6.3
LED 2002	125	25	3	75	60	6.0
LED 2023	1000 or more	150-300	10	90	60	< 1.0

Further development of incandescent and halogen bulbs

Tungsten filament with photonic band structure via 3D-structuring.

Aim: Reduction of the IR-emission and therefore increasing the light efficiency.



4.8 New Developments

Specialties

High performance lamps
(up to 20 kW)

Colored incandescent lamp
(coated with inorganic metal oxides)

with $CoAl_2O_4$

with Fe_2O_3

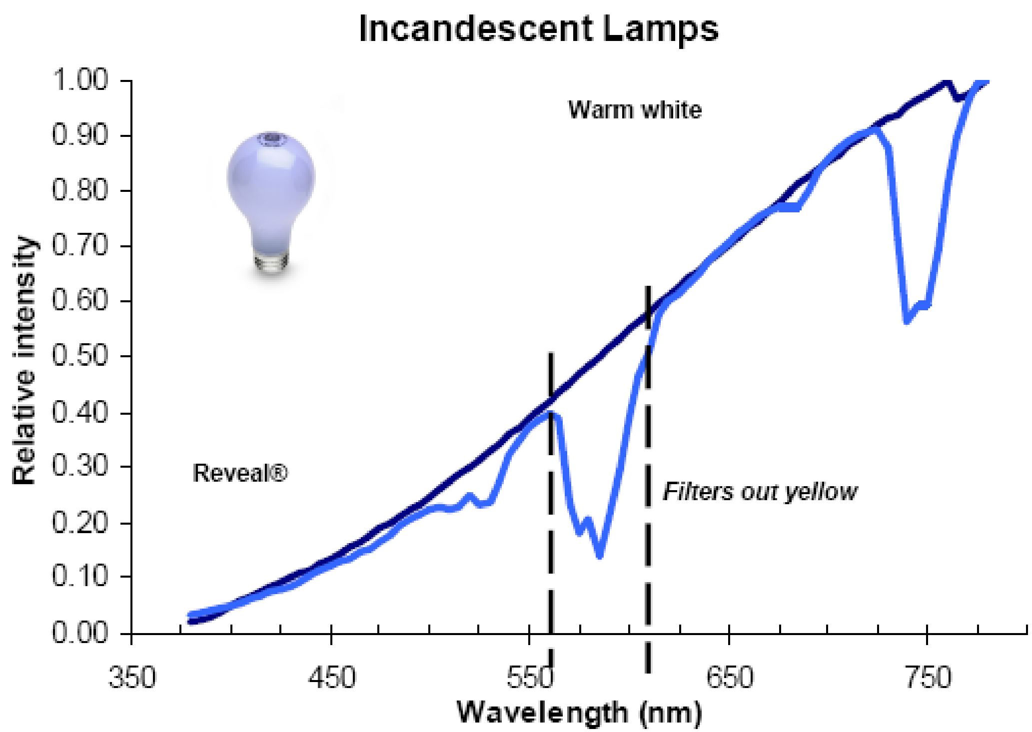
4.8 New Developments

Specialties

Doping of the lamp glass, e.g. by Nd_2O_3 (GE Lighting: Reveal®)

Aim: Increase of the color temperature without loss of color rendering

Enhancement of the contrast between red and green



4.8 New Developments

Specialties

Halogen lamp with color filter for heat therapy

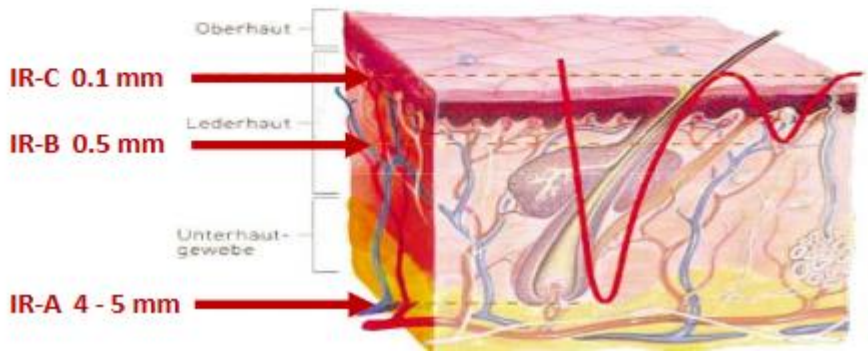
- Infrared penetrates deep into the skin
- Stimulates blood circulation and warms muscles

200 Watt infrared halogen lamp with color filter

https://www.philips.de/c-m-pe/schmerztherapie/p/infrarot-leuchten

Application areas

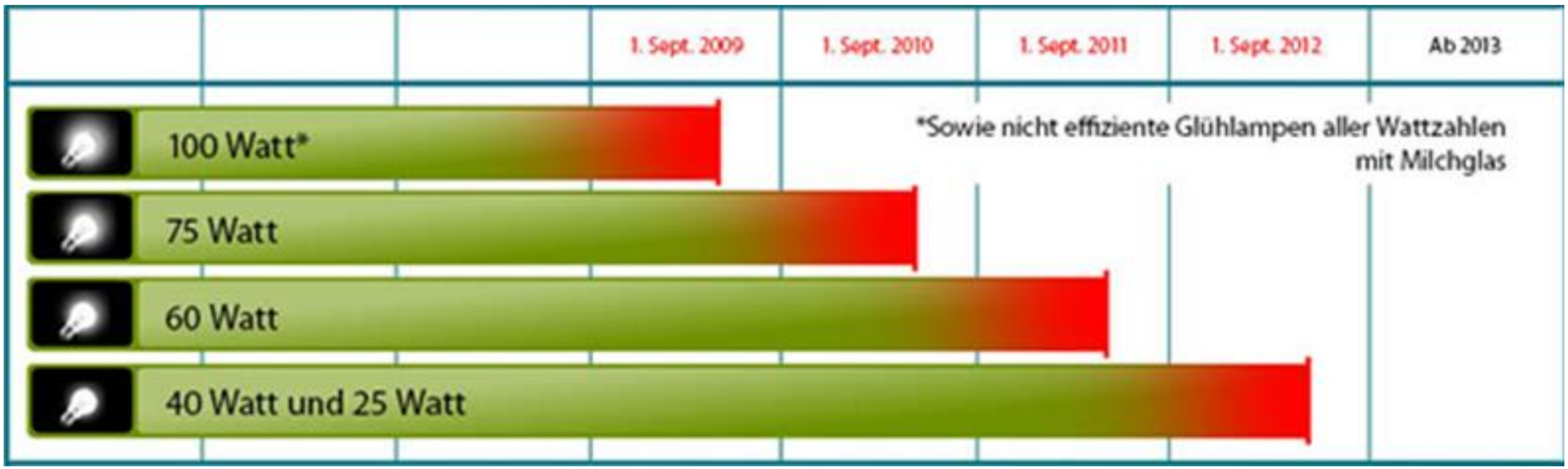
- back pain
- temperature regulation of newborn
- rheumatic diseases



4.8 New Developments

Specialties

2010: Marketing of incandescent lamps as heatballs, as a reaction on the ban of incandescent lamps driven by the EU



2016: Ban of halogen lamps implemented