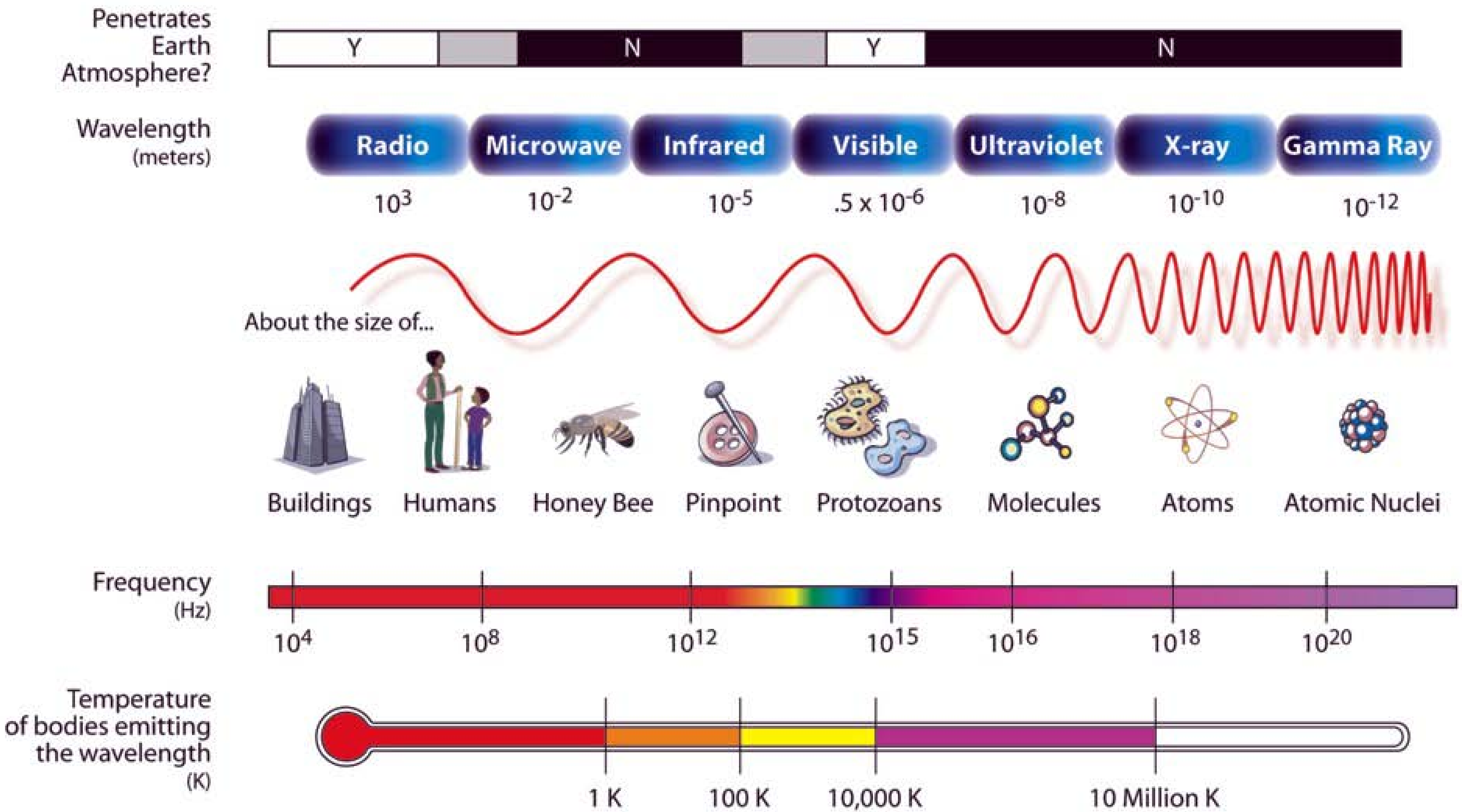
Blackbody Radiation and Optical Sources

Optical Engineering

Prof. Elias N. Glytsis

School of Electrical & Computer Engineering
National Technical University of Athens

THE ELECTROMAGNETIC SPECTRUM



Wave-Particle Duality of Light

De Broglie (1924): $\lambda = h / p$,

***h* = 6.62607015 × 10^{-34} J sec**, p = momentum

(exact according to **NIST 2018-2019**)

Φορτίο Ηλεκτρονίου: **e = 1.602176634 × 10^{-19} Coulombs** (exact value according to **NIST 2018-2019**)

Photons (zero rest mass)

$$\lambda = \frac{h}{p}$$

$$E = h\nu = \frac{hc}{\lambda}$$

$$E = pc$$

Particles (non-zero rest mass)

$$E = \sqrt{p^2c^2 + m_0^2c^4}$$

$$E = mc^2 = (KE) + m_0c^2$$

$$pc = \sqrt{(KE)^2 + 2(KE)m_0c^2}$$

$$m = m_0\frac{1}{\sqrt{1-(v/c)^2}}$$

$$\lambda = \frac{h}{p} = \frac{hc}{\sqrt{(KE)^2 + 2(KE)m_0c^2}}$$

https://physics.nist.gov/cgi-bin/cuu/Category?view=pdf&All+values.x=71&All+values.y=12

Light Sources

Incoherent Light Sources

Incandescent Sources

Blackbody Radiators

Discharge Lamps

Line (Spectral) Sources)

High-Intensity Sources

Fluorescent Lamps

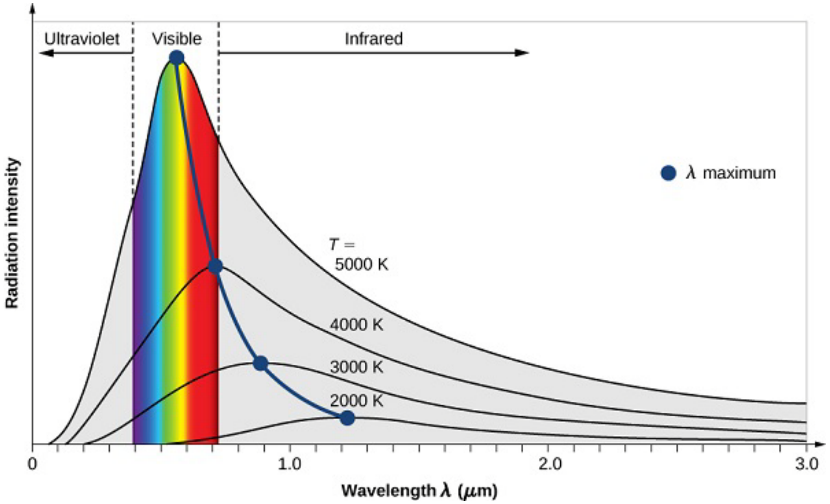
Light **E**mitting **D**iodes (LED)

Coherent Light Sources

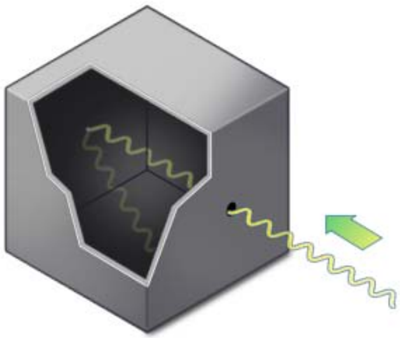
LASERS

(**L**ight **A**mplification via **S**timulated **E**mission of **R**adiation) (LASER)

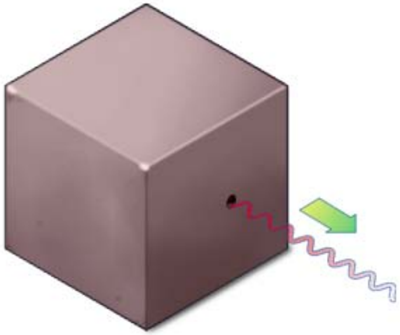
Blackbody Radiation



Blackbody Radiator



All incident radiation is absorbed



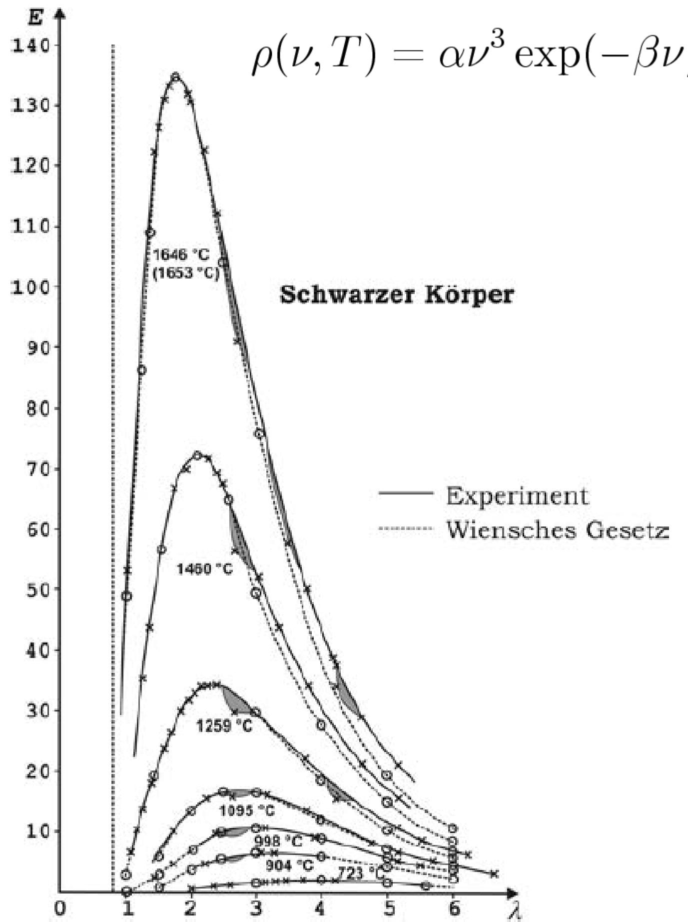
Emitted radiation is only a function of radiator's temperature (T)

https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Map%3A_Physical_Chemistry_(McQuarrie_and_Simon)/01%3A_The_Dawn_of_the_Quantum_Theory/1.01%3A_Blackbody_Radiation_Cannot_Be_Explained_Classically

Blackbody Radiation Measurements around 1900

Wien's Formula

$$\rho(\nu, T) = \alpha \nu^3 \exp(-\beta \nu / T)$$



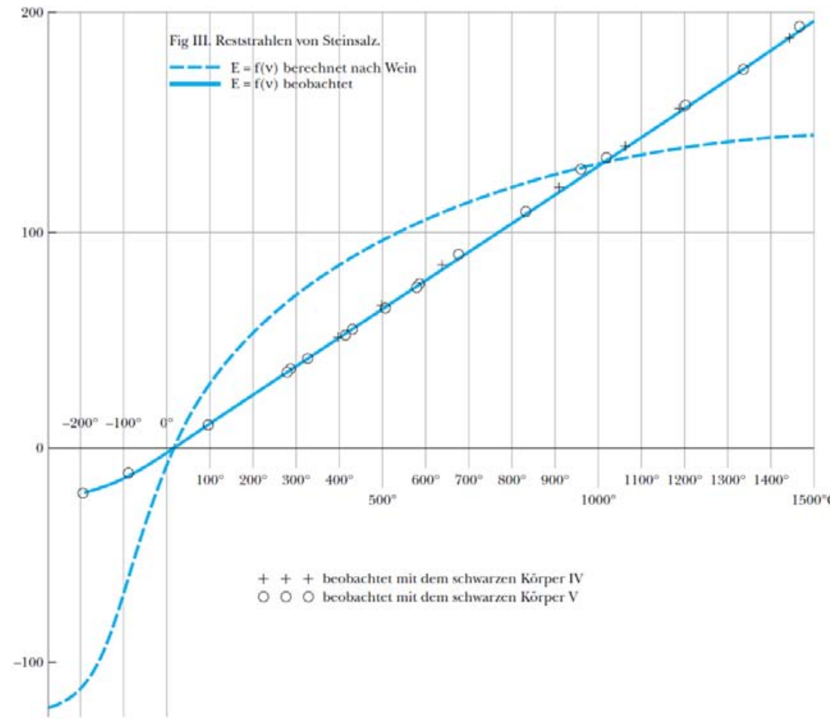


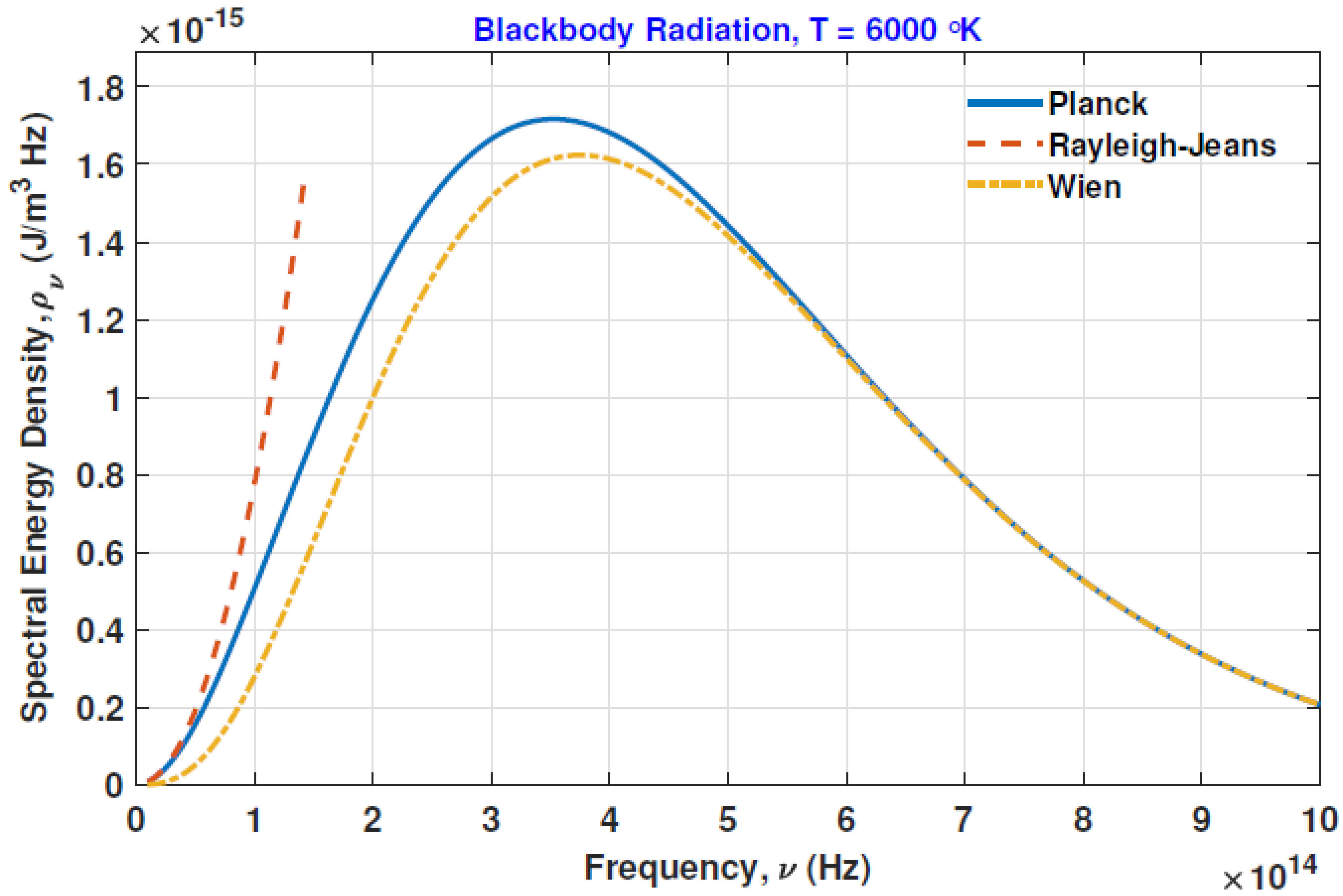
Figure 3.7 Comparison of theoretical and experimental blackbody emission curves at 51.2 μm and over the temperature range of $-188°$ to 1500°C. The title of this modified figure is "Residual Rays from Rocksalt." *Berechnet nach* means "calculated according to," and *beobachtet* means "observed." The vertical axis is emission intensity in arbitrary units. (*From H. Rubens and S. Kurlbaum,* Ann. Physik, *4:649, 1901.*)

Spectrum of the thermal radiation emitted by a blackbody, measured by **Lummer** and **Pringsheim** in 1900 and compared to Wien's radiation law

https://physlab.lums.edu.pk/images/e/e5/Phys_ref2.pdf

http://users.df.uba.ar/dmitnik/fisica4/articulos/cuantica/Lummer.pdf

Blackbody Radiation



Electromagnetic Cavity Modes

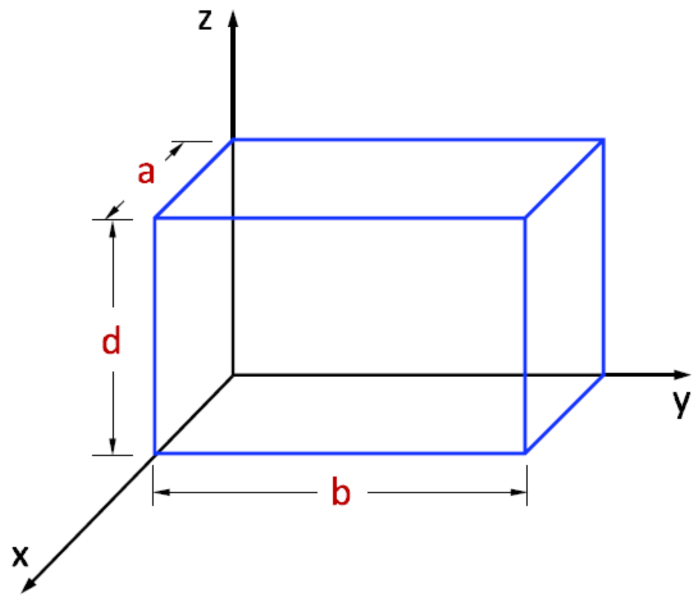
TE_{mpq} Modes

$$
\begin{aligned}
E_x &= C\frac{j\omega\mu_0}{k_c^2}\left(\frac{p\pi}{b}\right)\cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{p\pi}{b}y\right)\sin\left(\frac{q\pi}{d}z\right),\\
E_y &= -C\frac{j\omega\mu_0}{k_c^2}\left(\frac{m\pi}{a}\right)\sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{p\pi}{b}y\right)\sin\left(\frac{q\pi}{d}z\right),\\
E_z &= 0,\\
H_x &= -C\frac{1}{k_c^2}\left(\frac{m\pi}{a}\right)\left(\frac{q\pi}{d}\right)\sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{p\pi}{b}y\right)\cos\left(\frac{q\pi}{d}z\right),\\
H_y &= -C\frac{1}{k_c^2}\left(\frac{p\pi}{b}\right)\left(\frac{q\pi}{d}\right)\cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{p\pi}{b}y\right)\cos\left(\frac{q\pi}{d}z\right),\\
H_z &= C\cos\left(\frac{m\pi}{a}x\right)\cos\left(\frac{p\pi}{b}y\right)\sin\left(\frac{q\pi}{d}z\right).
\end{aligned}
$$

TM_{mpq} Modes

$$
\begin{aligned}
E_x &= -D\frac{1}{k_c^2}\left(\frac{m\pi}{a}\right)\left(\frac{q\pi}{d}\right)\cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{p\pi}{b}y\right)\sin\left(\frac{q\pi}{d}z\right),\\
E_y &= -D\frac{1}{k_c^2}\left(\frac{p\pi}{b}\right)\left(\frac{q\pi}{d}\right)\sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{p\pi}{b}y\right)\sin\left(\frac{q\pi}{d}z\right),\\
E_z &= D\sin\left(\frac{m\pi}{a}x\right)\sin\left(\frac{p\pi}{b}y\right)\cos\left(\frac{q\pi}{d}z\right),\\
H_x &= D\frac{j\omega\epsilon_0 n^2}{k_c^2}\left(\frac{p\pi}{b}\right)\sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{p\pi}{b}y\right)\cos\left(\frac{q\pi}{d}z\right),\\
H_y &= -D\frac{j\omega\epsilon_0 n^2}{k_c^2}\left(\frac{m\pi}{a}\right)\cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{p\pi}{b}y\right)\cos\left(\frac{q\pi}{d}z\right),\\
H_z &= 0.
\end{aligned}
$$

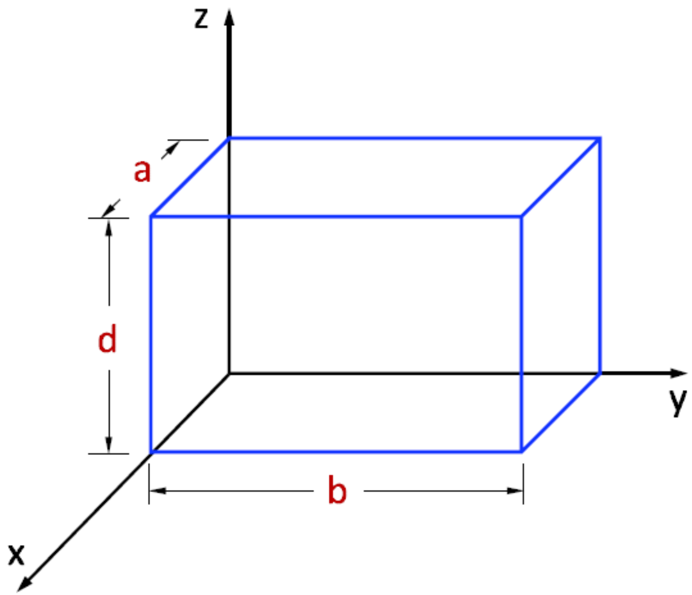
From Maxwell's equations
Electromagnetic Knowledge

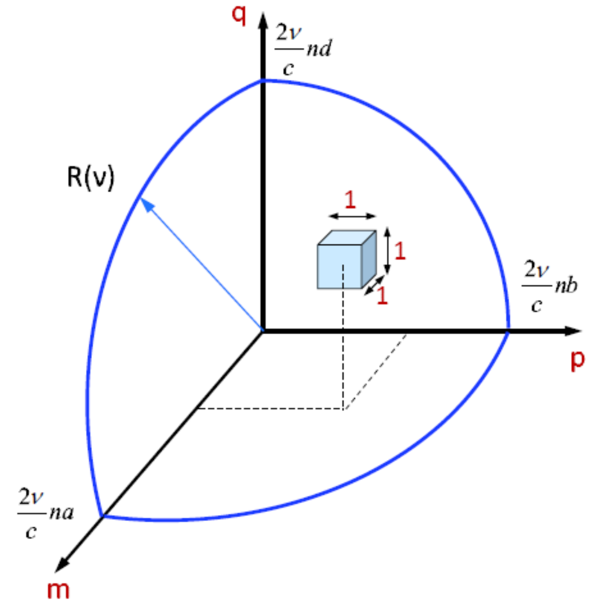


Dispersion Relation

$$
\begin{aligned}
k_0^2 n^2 &= \left(\frac{m\pi}{a}\right)^2 + \left(\frac{p\pi}{b}\right)^2 + \left(\frac{q\pi}{d}\right)^2,\\
\omega_{mnq} &= \frac{c}{n}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{p\pi}{b}\right)^2 + \left(\frac{q\pi}{d}\right)^2}.
\end{aligned}
$$

Blackbody Radiation





$$\left(\frac{m\pi}{a}\right)^2 + \left(\frac{p\pi}{b}\right)^2 + \left(\frac{q\pi}{d}\right)^2 = \left(\frac{2\pi\nu}{c}\right)^2 n^2$$

$$m^2 + p^2 + q^2 = \left(\frac{2\nu}{c}\right)^2 a^2 n^2 = \left(\frac{2\nu n a}{c}\right)^2$$

$$N(\nu) = \frac{(1/8)\text{ cavity volume}}{\text{volume of a mode}} = \frac{(1/8)(4/3)\pi(2\nu a n/c)^3}{1\times 1\times 1} = \frac{4}{3}\pi\frac{\nu^3 n^3 a^3}{c^3}$$

$$\mathcal{N}(\nu) = \frac{N(\nu)}{Volume = a^3} = \frac{8}{3}\pi\frac{\nu^3 n^3}{c^3}$$

Density of Electromagnetic Modes per Frequency:

$$\frac{d\mathcal{N}(\nu)}{d\nu} = \frac{8\pi\nu^2 n^3}{c^3}$$

Blackbody Radiation

From Boltzmann's statistics (energy of an *em*-mode between E and E+dE):

$$p(E)dE = A\exp\left(-\frac{E}{k_B T}\right)dE$$

Boltzmann's Constant

$$k_B = 1.380649 \times 10^{-23}\ J/^\circ K$$

Normalization $\int_0^\infty p(E)dE = 1 \Longrightarrow A = \frac{1}{\int_0^\infty \exp(-E/k_B T)dE} = \frac{1}{k_B T}$

Average Energy per Electromagnetic Mode:

$$\langle E\rangle = \int_0^\infty E p(E)dE = \int_0^\infty E\frac{1}{k_B T}\exp\left(-\frac{E}{k_B T}\right)dE = k_B T$$

Rayleigh-Jeans Equation

$$\rho(\nu, T) = \frac{dN(\nu)}{d\nu}k_B T = \frac{8\pi\nu^2 n^3}{c^3}k_B T$$

Blackbody Radiation

Planck's Equation

$$\rho(\nu, T) = \frac{8\pi\nu^2 n^3}{c^3} \frac{h\nu}{\exp(h\nu/k_B T) - 1}$$

Planck's Energy Quantization $E_i = ih\nu$ $\quad i = 0, 1, 2, \cdots$

Boltzmann Statistics – Discrete Energy States

$$p(E_i) = A \exp\left(-\frac{E_i}{k_B T}\right)$$

$$\sum_{i=0}^{\infty} p(E_i) = 1 \Longrightarrow A = \frac{1}{\sum_{i=0}^{\infty} \exp(-E_i/k_B T)} = 1 - \exp\left(-\frac{h\nu}{k_B T}\right)$$

$$\begin{aligned}\langle E \rangle &= A \sum_{i=0}^{\infty} E_i \exp\left(-\frac{E_i}{k_B T}\right) = A\left[1h\nu e^{-h\nu/k_B T} + 2h\nu e^{-2h\nu/k_B T} + \cdots\right] = \\ &= A \frac{h\nu \exp(-h\nu/k_B T)}{[1 - \exp(-h\nu/k_B T)]^2} = \frac{h\nu}{\exp(h\nu/k_B T) - 1}.\end{aligned}$$

Blackbody Radiation

$$\rho(\nu,T) = \underbrace{\frac{8\pi\nu^2 n^3}{c^3}}_{\substack{\text{Number of em modes}\\ \text{per volume per frequency}}} \overbrace{h\nu}^{\text{photon energy}} \underbrace{\frac{1}{\exp(h\nu/k_B T)-1}}_{\text{Number of photons/mode}}$$

Spectral Power per Unit Area

$$dP_{avg} = \frac{8\pi n^2\nu^2}{c^2}\frac{h\nu}{\exp(h\nu/k_BT)-1}d\nu = P_{avg,\nu}d\nu,$$

$$dP_{avg} = \frac{8\pi n^2 c}{\lambda_0^4}\frac{hc/\lambda_0}{\exp(hc/\lambda_0 k_BT)-1}d\lambda_0 = P_{avg,\lambda_0}d\lambda_0$$

Spectral Radiant *Exitance* per Frequency (W/m^{2}Hz)

$$M_\nu(\nu) = \frac{2\pi n^2\nu^2}{c^2}\frac{h\nu}{\exp(h\nu/k_BT)-1}$$

$$M_{\lambda_0} = \frac{2\pi n^2 c}{\lambda_0^4}\frac{hc/\lambda_0}{\exp(hc/\lambda_0 k_BT)-1},$$

$$M_\lambda = \frac{2\pi c}{n^2\lambda^4}\frac{hc/\lambda}{\exp(hc/\lambda n k_BT)-1}.$$

Blackbody Radiation

Stefan-Boltzmann Law

$$M = \int_0^\infty M_{\lambda_0} d\lambda_0 = \left(\frac{2\pi^5 k_B^4}{15h^3c^2}\right) n^2 T^4 = \sigma n^2 T^4$$

$$\sigma = 5.670374419 \times 10^{-8} \frac{W}{m^2 \circ K^4}$$

Wien's Displacement Law

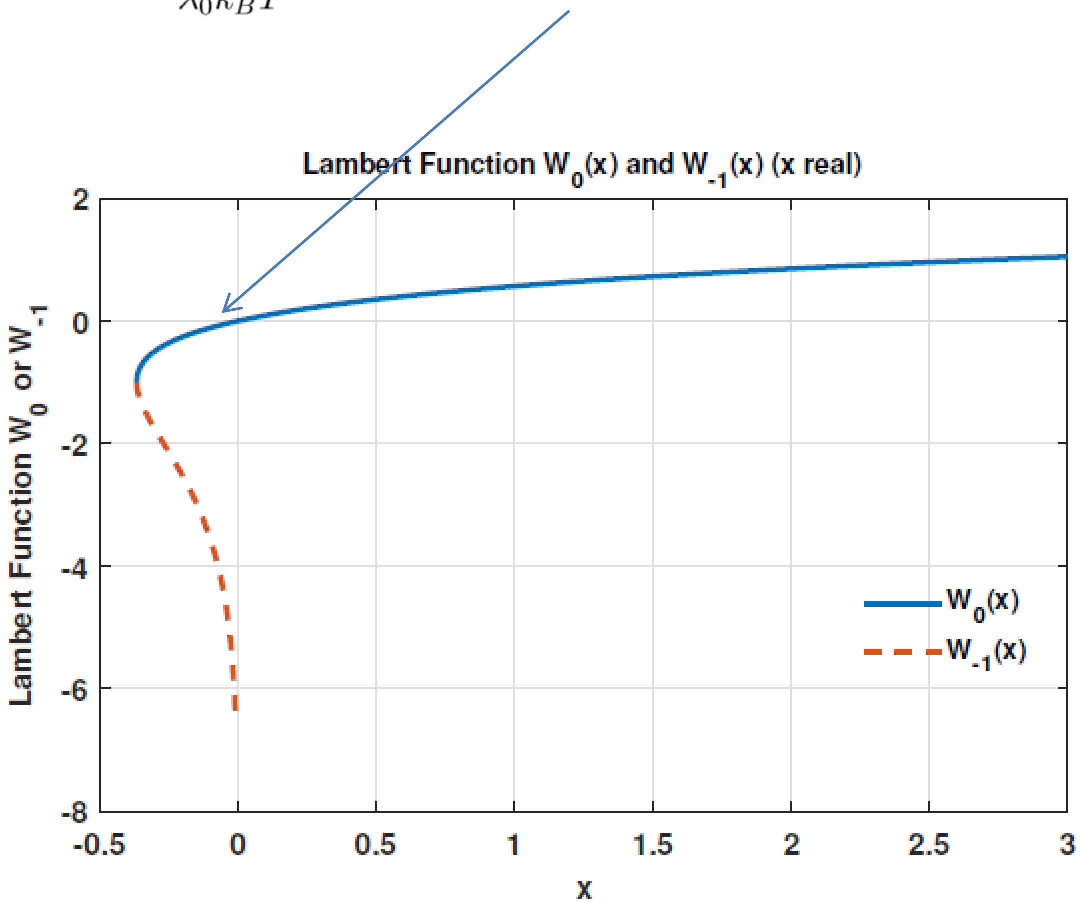
$$\frac{dM_{\lambda_0}(\lambda_{0,max})}{d\lambda_0} = 0 \Rightarrow \frac{hc}{\lambda_{0,max} k_B T} = 4.965114231 \Rightarrow \lambda_{0,max} T = 2897.772\, \mu m^\circ K$$

$$\frac{dM_\nu(\nu_{max})}{d\nu} = 0 \Rightarrow \frac{h\nu_{max}}{k_B T} = 2.82143937 \Rightarrow \frac{\nu_{max}}{T} = 5.878926 \times 10^{10}\; Hz/^\circ K.$$

Wien's Displacement Law - Use of Lambert Function

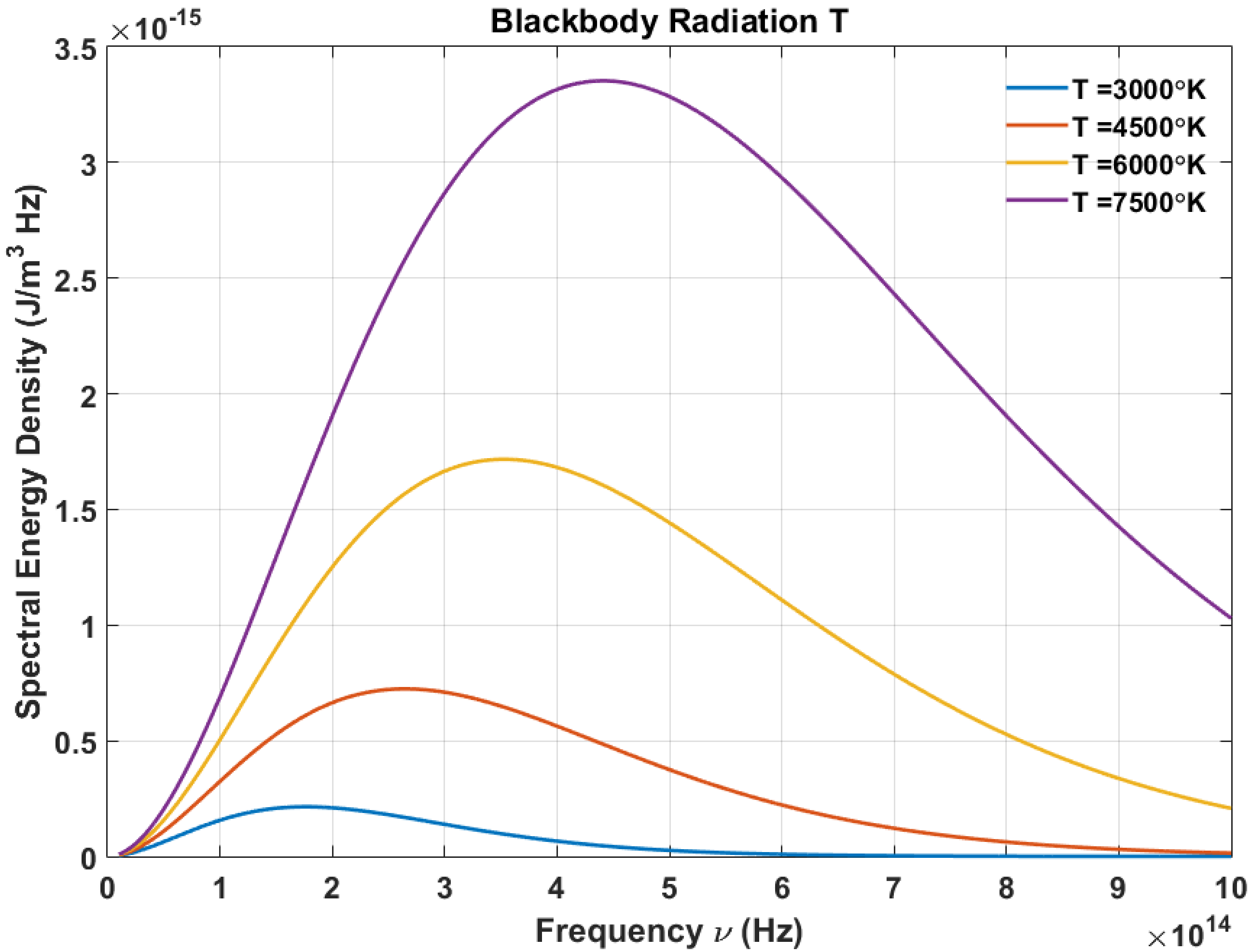
$$\frac{dM_{\lambda_0}}{d\lambda_0} = 0 \implies xe^x - 5e^x + 5 = 0 \implies$$

$$\frac{hc}{\lambda_0 k_B T} = x = 5 + W_0(-5e^{-5}) = 4.965114231$$



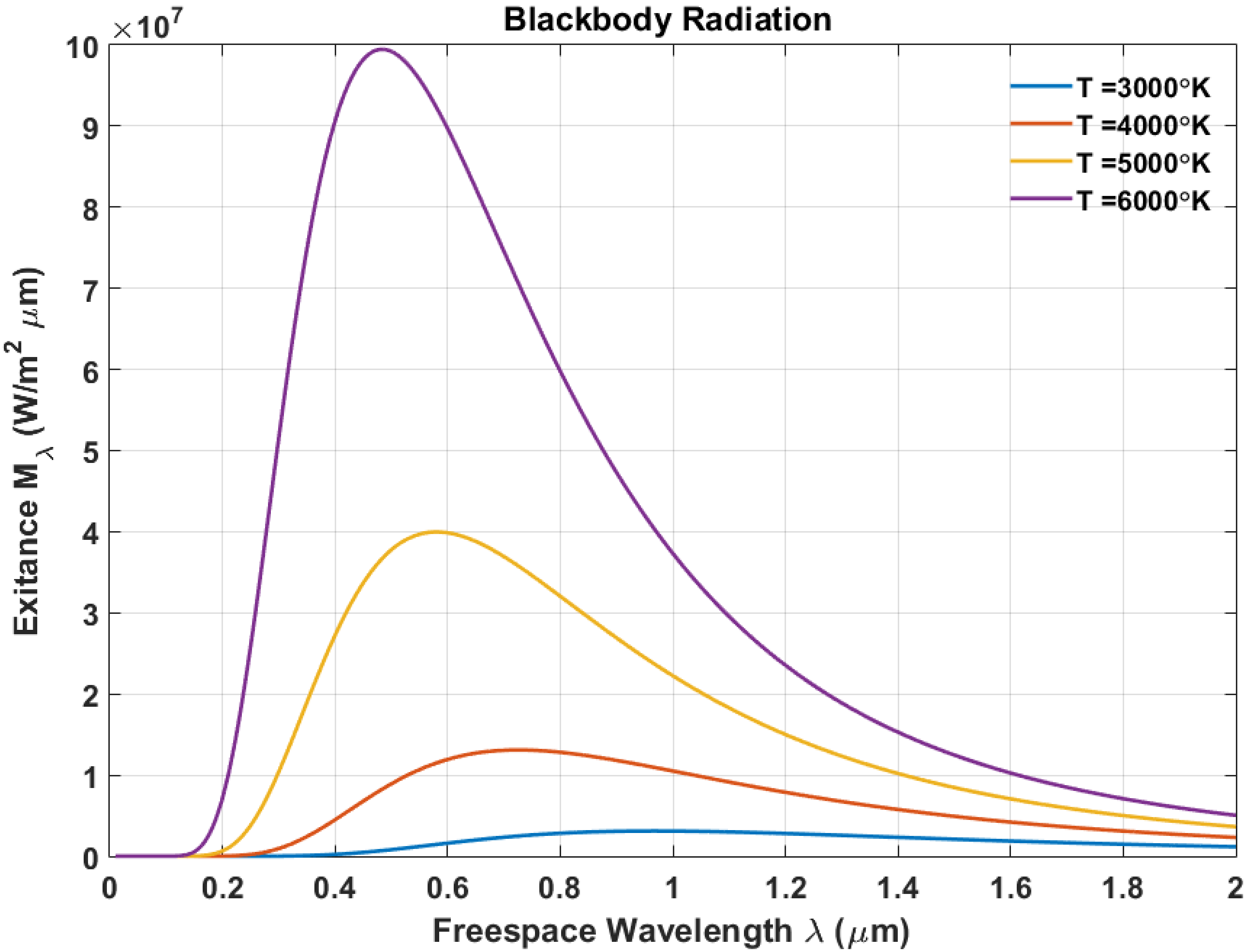
Blackbody Radiation

$$\rho(\nu, T) = \frac{8\pi\nu^2 n^3}{c^3} \frac{h\nu}{\exp(h\nu/k_B T) - 1}$$

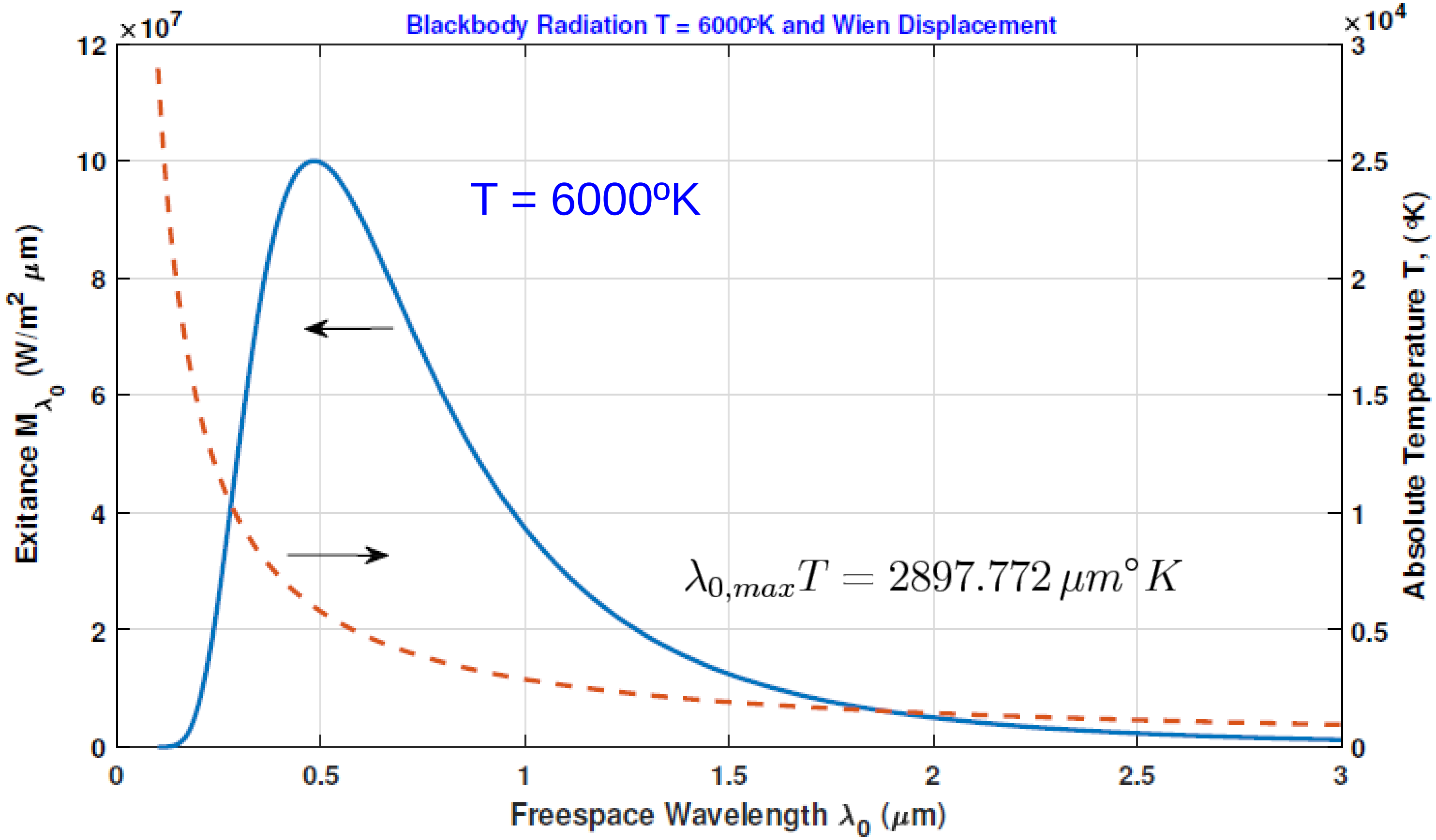


Blackbody Radiation

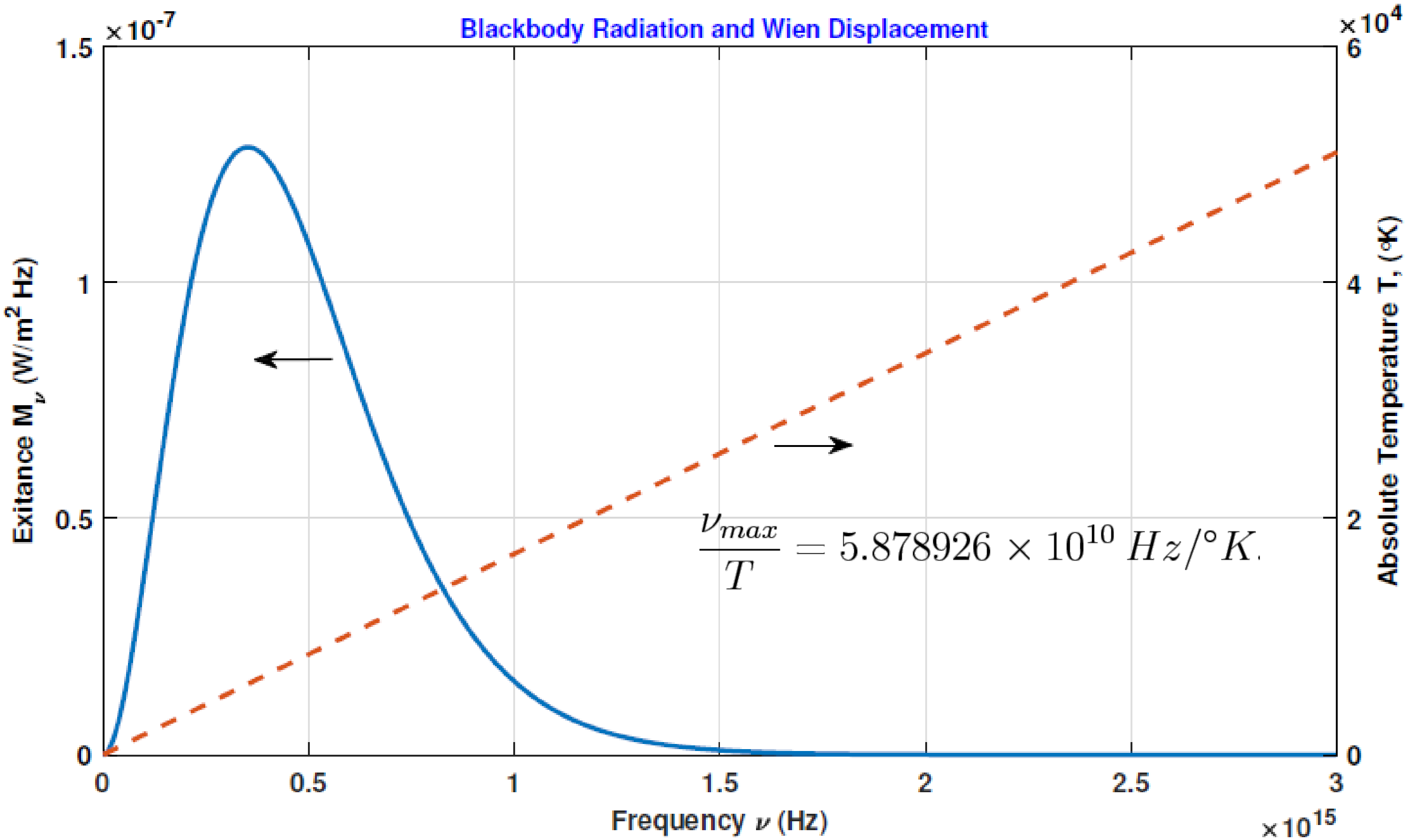
$$M_\lambda = \frac{2\pi n^2 c}{\lambda^4} \frac{hc/\lambda}{\exp(hc/\lambda k_B T) - 1}$$



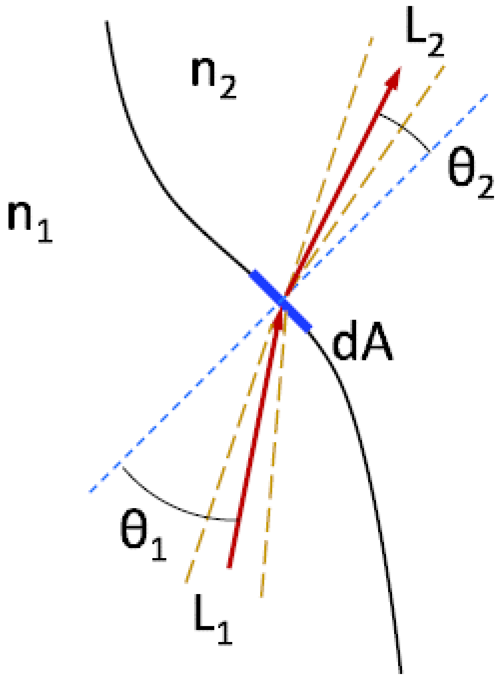
Blackbody Radiation – Spectral Exitance



Blackbody Radiation – Spectral Exitance



Blackbody Radiation – *Radiance Conservation*



Stefan-Boltzmann Law $M = \int_0^\infty M_{\lambda_0} d\lambda_0 = \left(\frac{2\pi^5 k_B^4}{15h^3c^2}\right) n^2 T^4 = \sigma n^2 T^4$

Neglecting Reflections

$$d^2P_1 = L_1 \cos\theta_1 dA \sin\theta_1 d\theta_1 d\phi = d^2P_2 = L_2 \cos\theta_2 dA \sin\theta_2 d\theta_2 d\phi \Longrightarrow$$

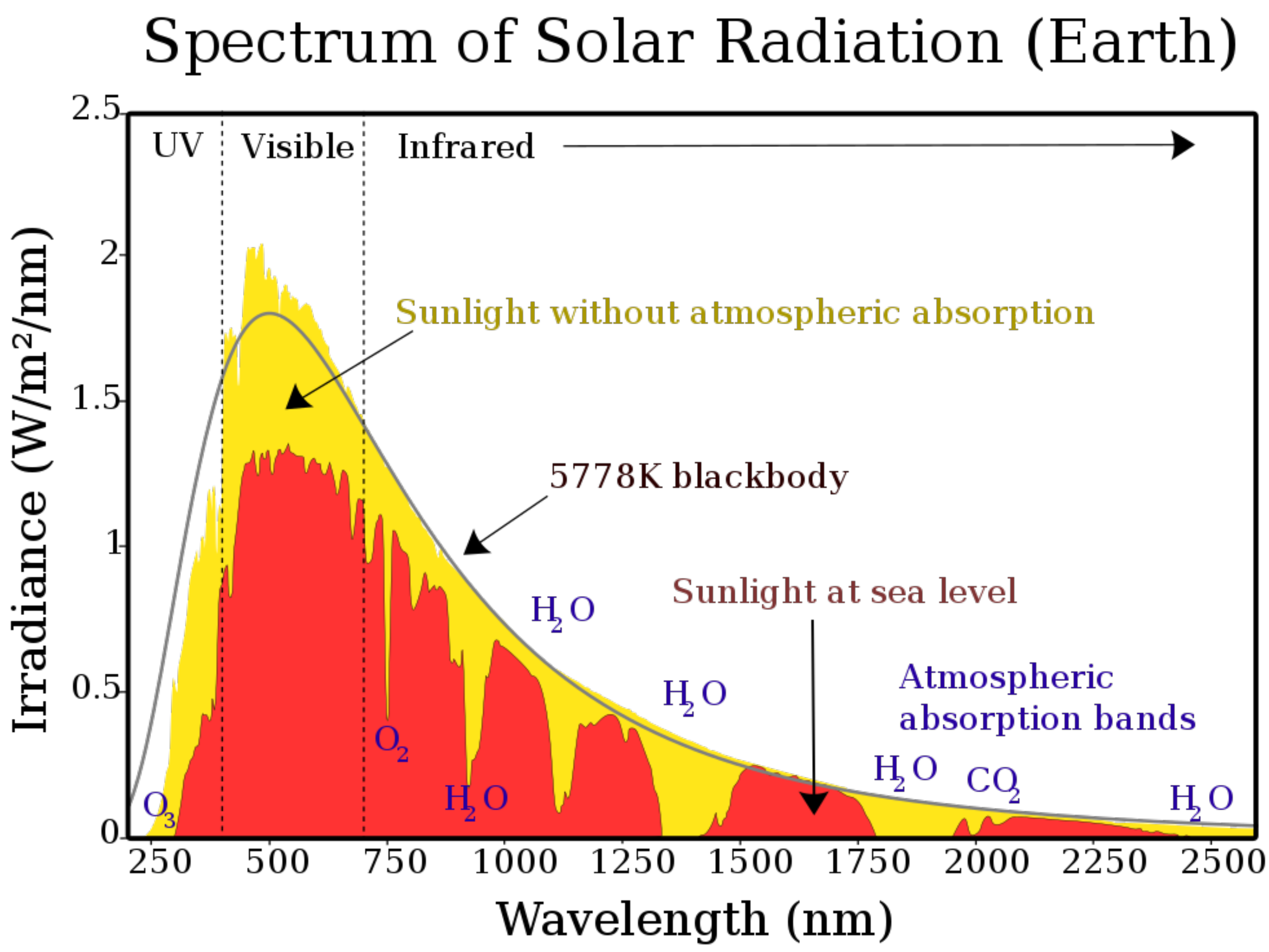
$$L_1 = L_2 \frac{\cos\theta_2 d\theta_2}{\cos\theta_1 d\theta_1} \frac{\sin\theta_2}{\sin\theta_1} = L_2 \frac{n_1^2}{n_2^2} \Longrightarrow$$

$$\boxed{\frac{L_1}{n_1^2} = \frac{L_2}{n_2^2} = L_0} \Longleftrightarrow \boxed{\frac{M_1}{n_1^2} = \frac{M_2}{n_2^2} = M_0,}$$

However Total Internal Reflection occurs

$$dP = \int_0^{2\pi}\int_0^{\theta_{max}} L_i dA \cos\theta \sin\theta d\phi d\theta = 2\pi L_i dA \frac{\sin^2\theta_{max}}{2}$$

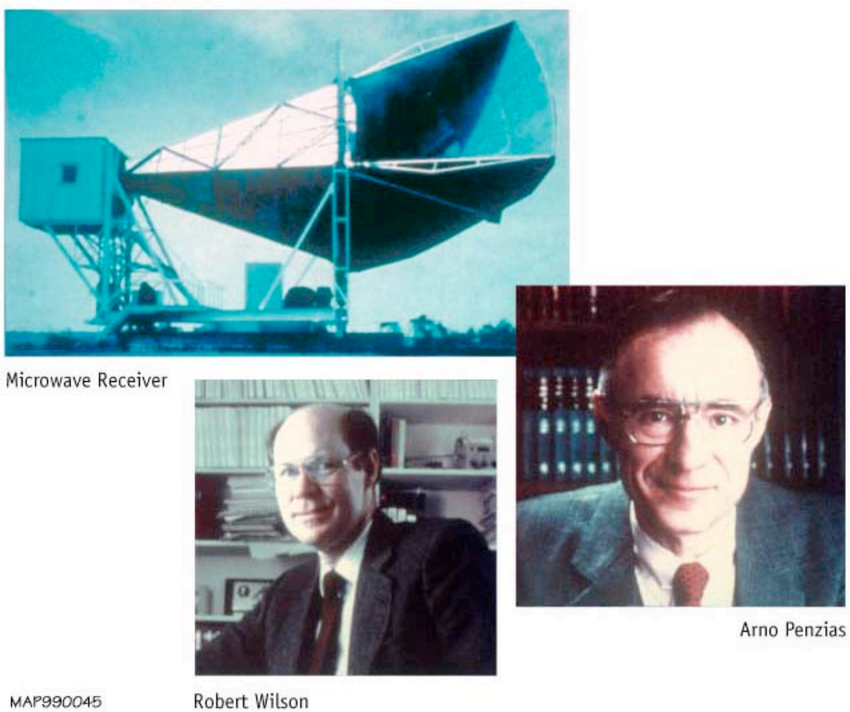
$$= \pi L_i dA \frac{1}{n_i^2} = \frac{M_i}{n_i^2} dA = M_0 dA,$$

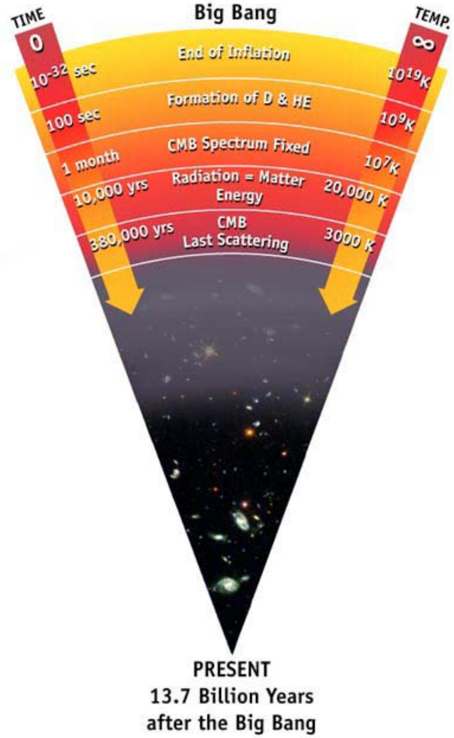


https://upload.wikimedia.org/wikipedia/commons/thumb/e/e7/Solar_spectrum_en.svg/1024px-Solar_spectrum_en.svg.png

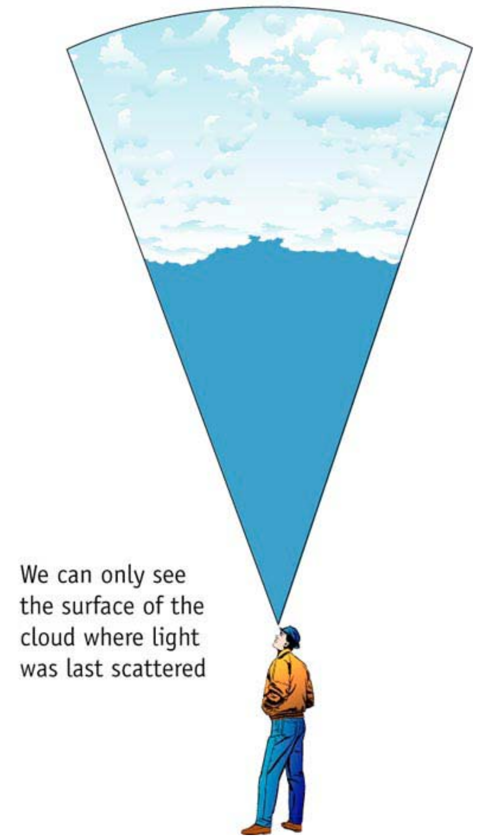
Discovery of Cosmic Background Radiation

It was first observed inadvertently in **<u>1965</u>** by Arno Penzias and Robert Wilson at the Bell Telephone Laboratories in Murray Hill, New Jersey.





The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

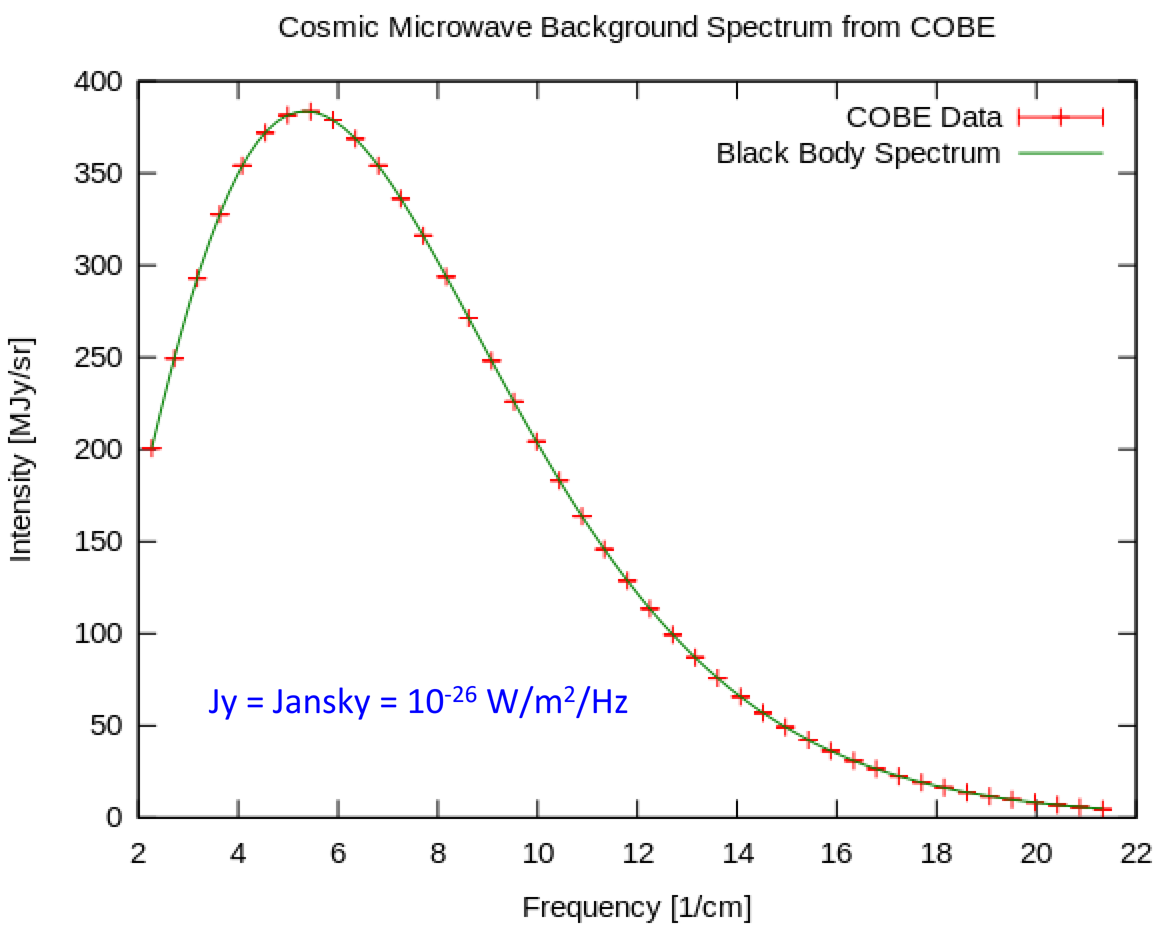


<u>A. Penzias</u> and <u>R. Wilson</u> shared the **1978 Nobel prize** in physics for their discovery.

http://map.gsfc.nasa.gov/universe/bb_tests_cmb.html

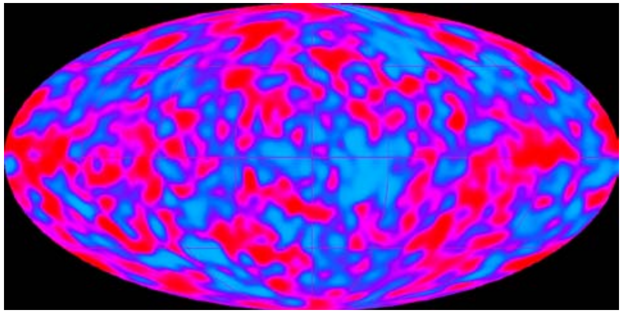
<u>CO</u>smic <u>B</u>ackground <u>E</u>xplorer (COBE)

Data from COBE showed a perfect fit between the blackbody curve predicted by <u>Big-Bang Theory</u> and that observed in the microwave background. $T = 2.725$ K, $\nu_{max} = 160.29$GHz, ($\lambda_0 = 1.870$mm)



Jy = Jansky = 10^{-26} W/m^2/Hz

Arno Penzias & Robert Wilson
Nobel Prize 1978



The famous map of the CMB anisotropy formed from data taken by the COBE spacecraft.

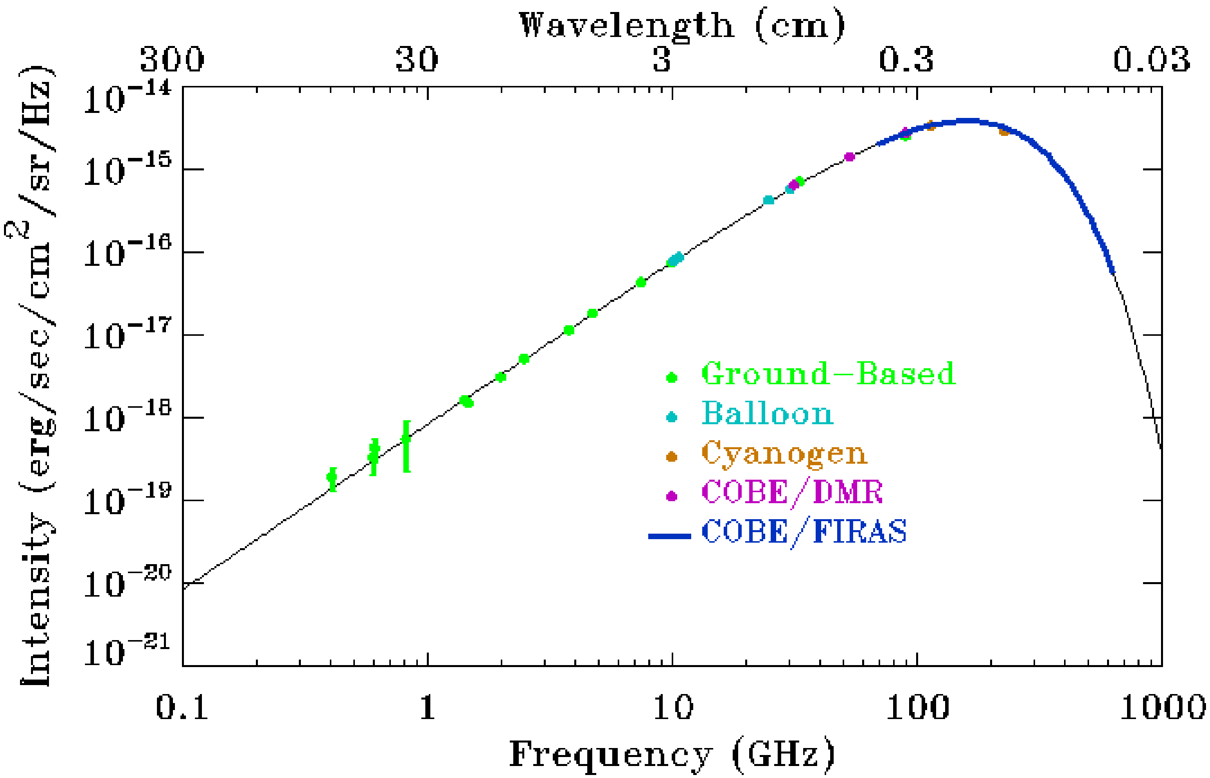
The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today.

https://en.wikipedia.org/wiki/Cosmic_Background_Explorer

COsmic Background Explorer (COBE)

Data from COBE showed a perfect fit between the blackbody curve predicted by Big-Bang Theory and that observed in the microwave background.

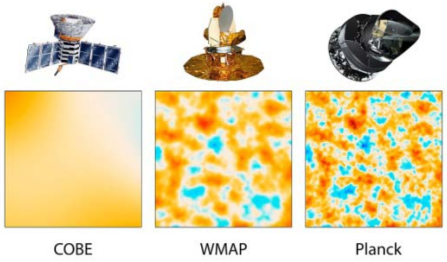
$T = 2.725$ K, $\nu_{max} = 160.29$GHz ($\lambda_0 = 1.870$mm)

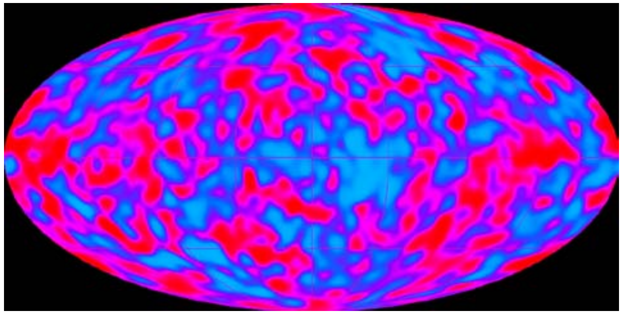


The most precise measurements of the CMB spectrum at the millimeter wavelengths near its peak were made by the Far Infrared Asbolute Spectrophotometer (FIRAS) instrument aboard the Cosmic Background Explorer (COBE) satellite. FIRAS determined the CMB temperature to be 2.725 +/- 0.001 K, with deviations from a perfect blackbody limited to less than 50 parts per million in intensity.

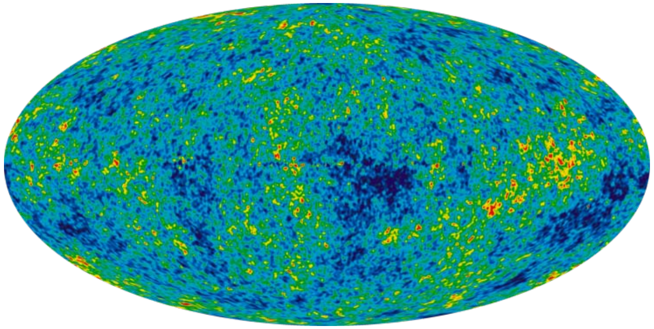
http://asd.gsfc.nasa.gov/archive/arcade/cmb_intensity.html

Cosmic Background Radiation



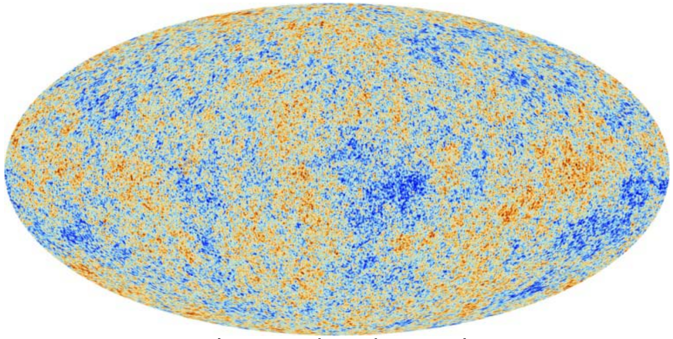


The famous map of the CMB anisotropy formed from data taken by the COBE spacecraft.



All-sky mollweide map of the CMB, created from 9 years of WMAP data

https://en.wikipedia.org/wiki/Cosmic_microwave_background



Cosmic Background Radiation by PLANK spacecraft (ESA) 2013.

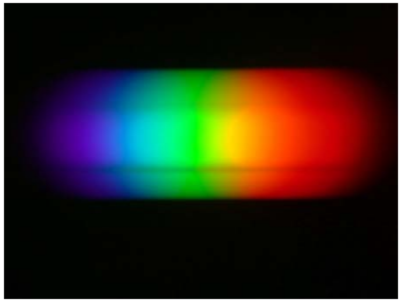
https://www.esa.int/Science_Exploration/Space_Science/Planck/Planck_and_the_cosmic_microwave_background

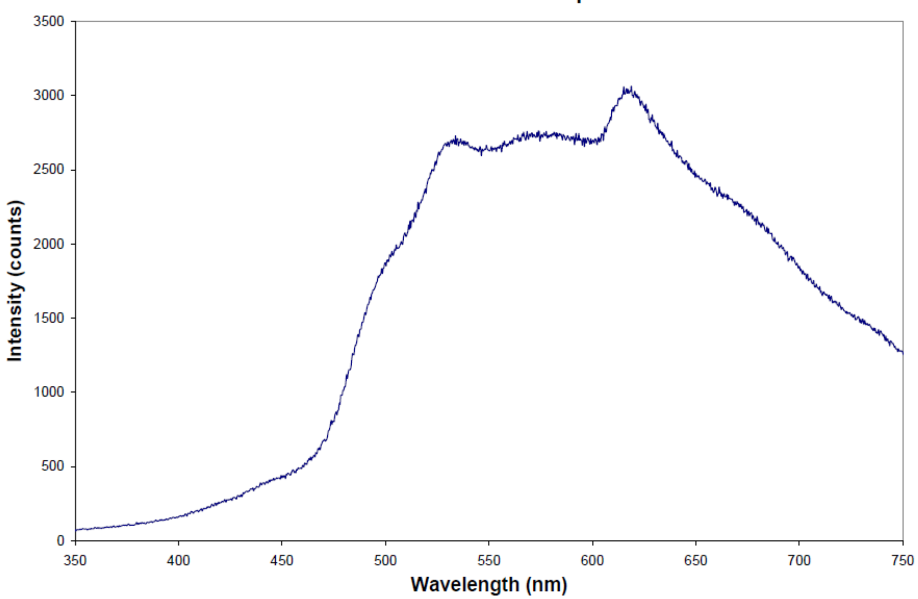
Temperature Anisotropy
dT/T ~ 1/100000 or 1/1000000

Incandescent Lamp

Lamp

Spectrum



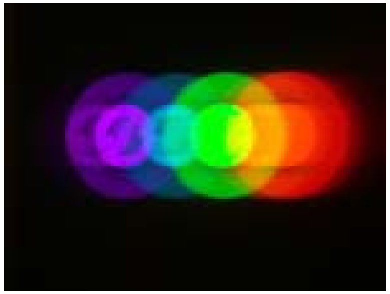


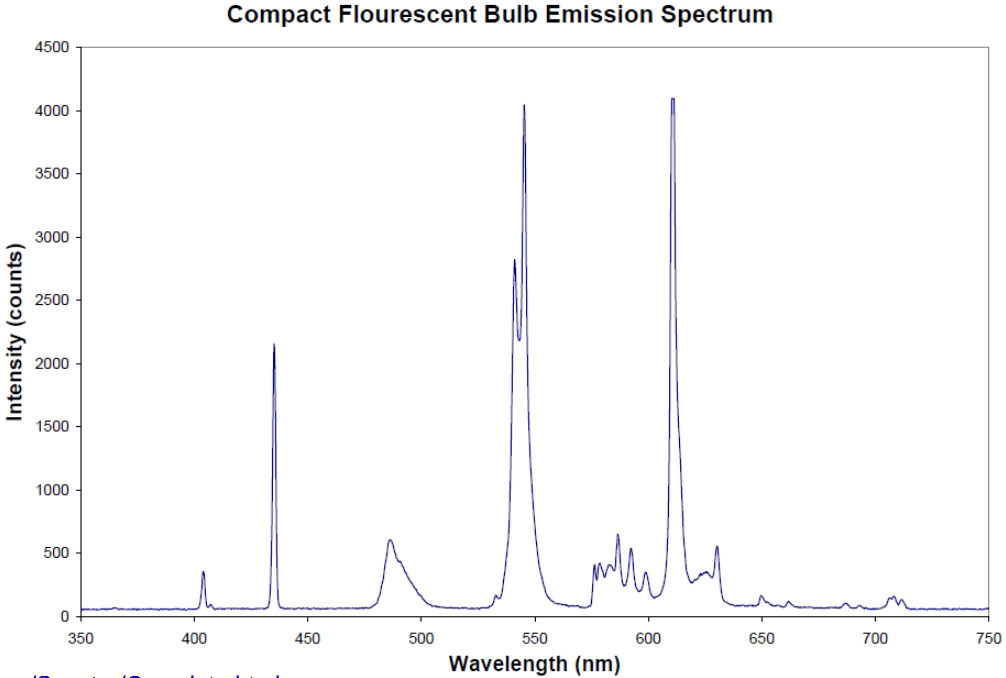
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

Compact Fluorescent Lamp

Lamp

Spectrum

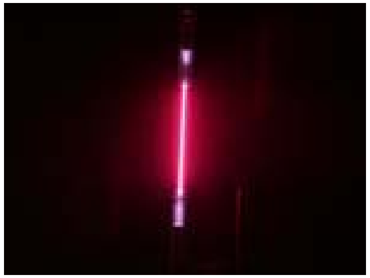




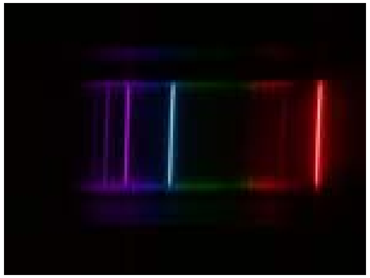
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

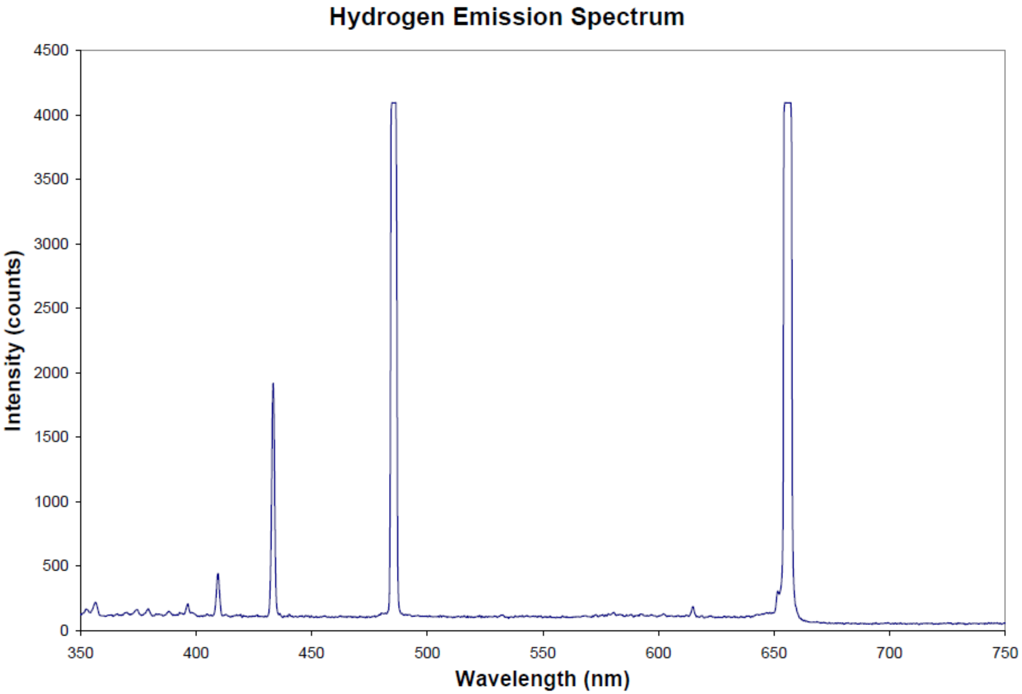
Hydrogen Lamp

Lamp



Spectrum

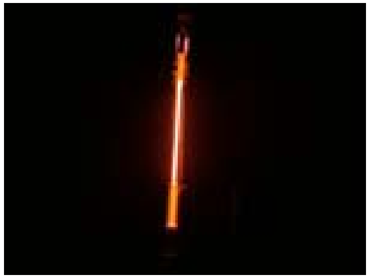




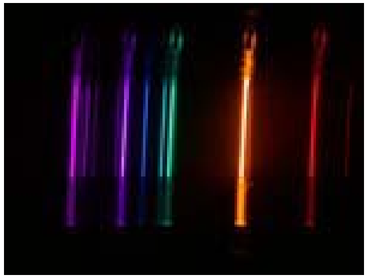
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

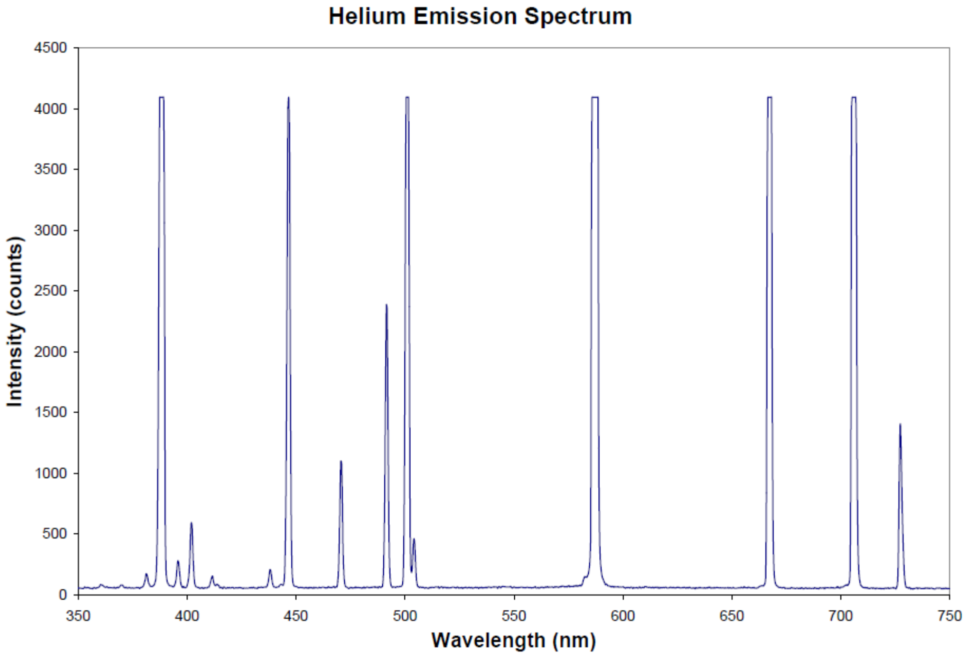
Helium Lamp

Lamp



Spectrum

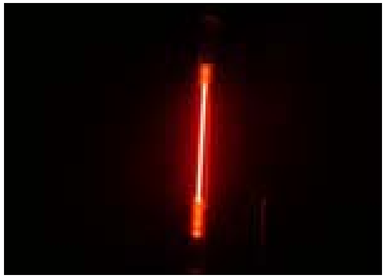




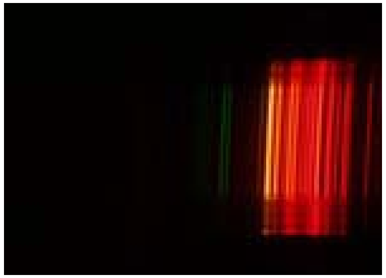
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

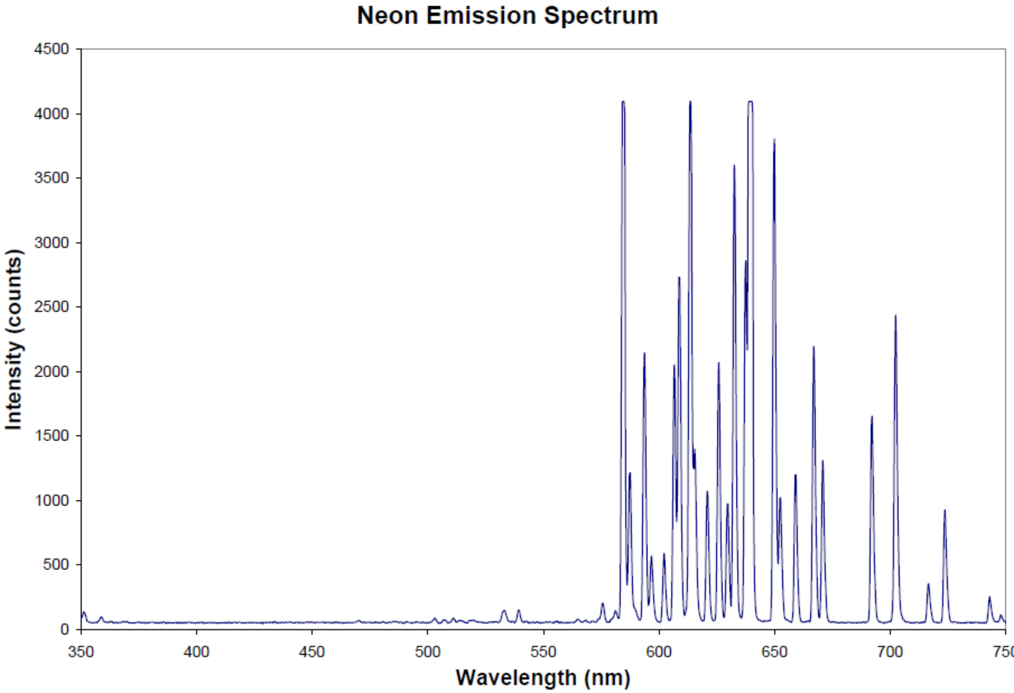
Neon Lamp

Lamp



Spectrum

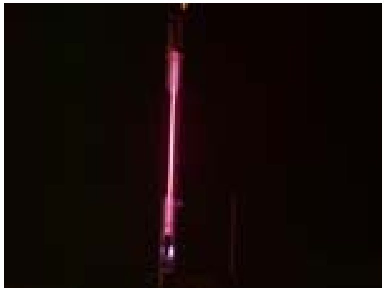




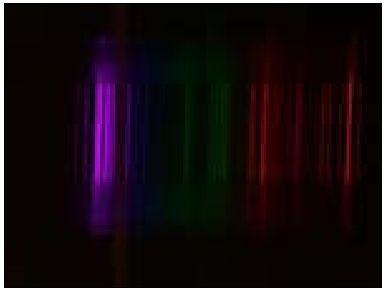
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

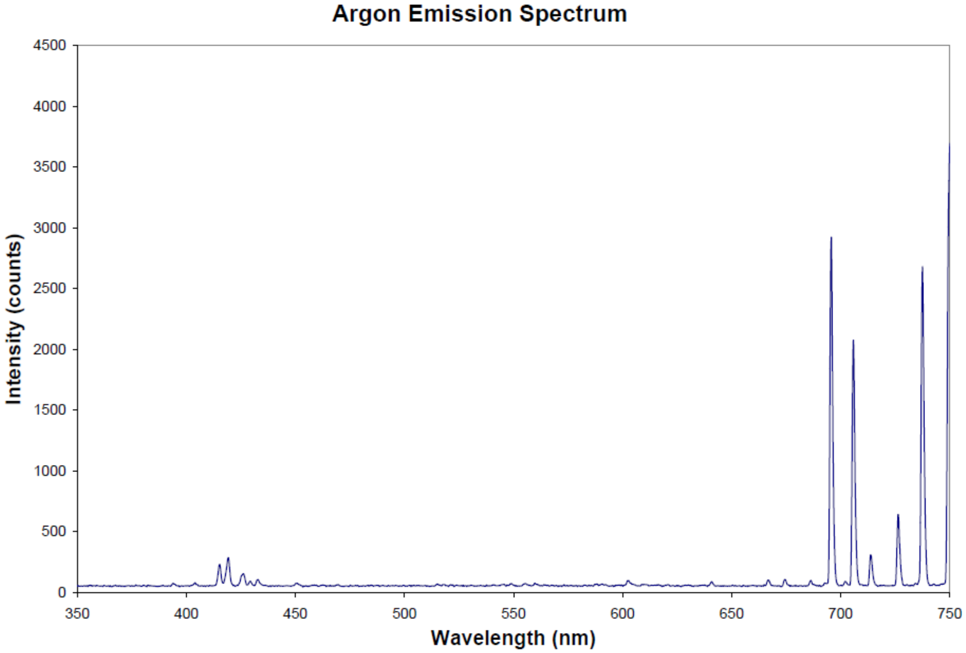
Argon Lamp

Lamp



Spectrum



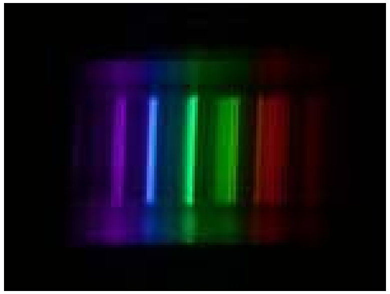


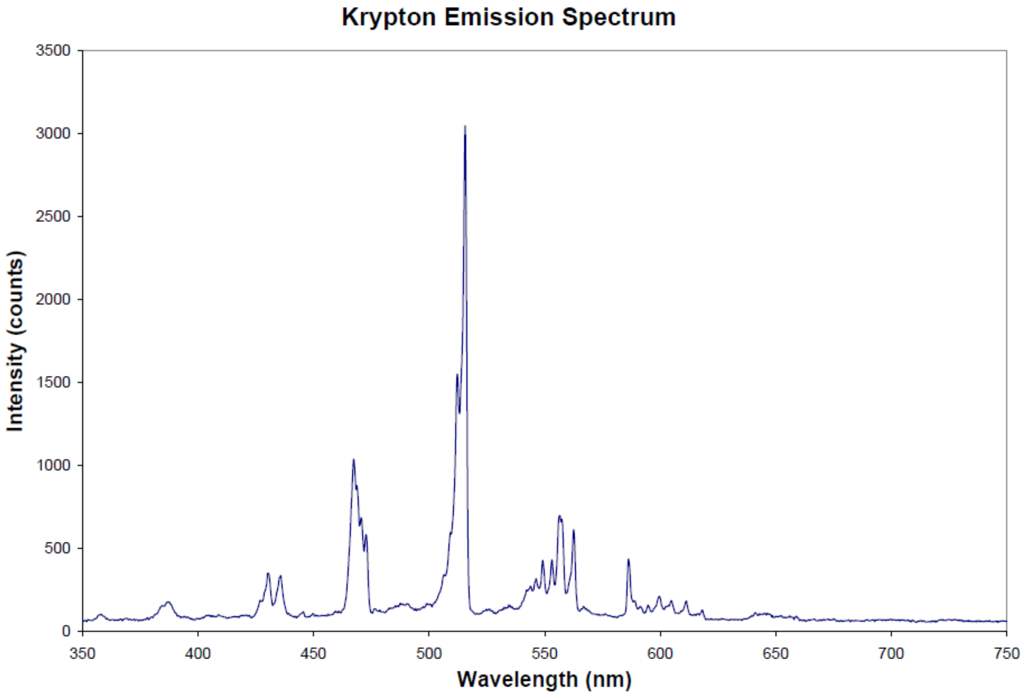
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

Krypton Lamp

Lamp

Spectrum



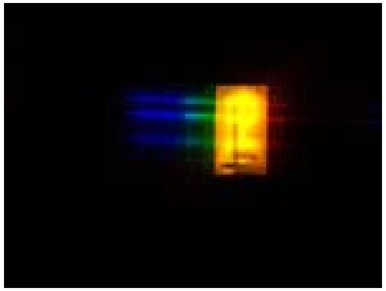


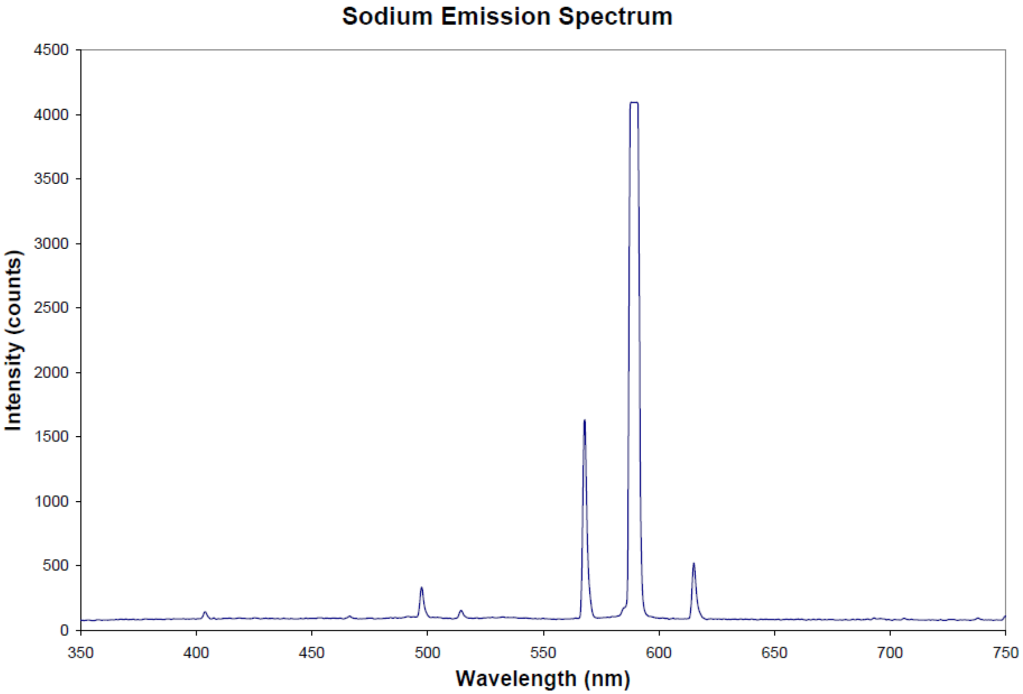
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

Sodium Lamp

Lamp

Spectrum

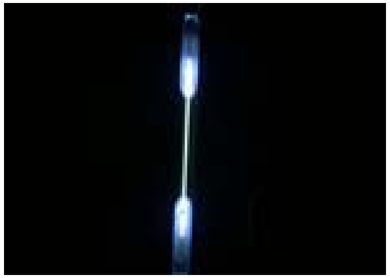




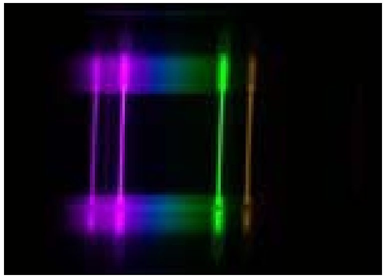
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

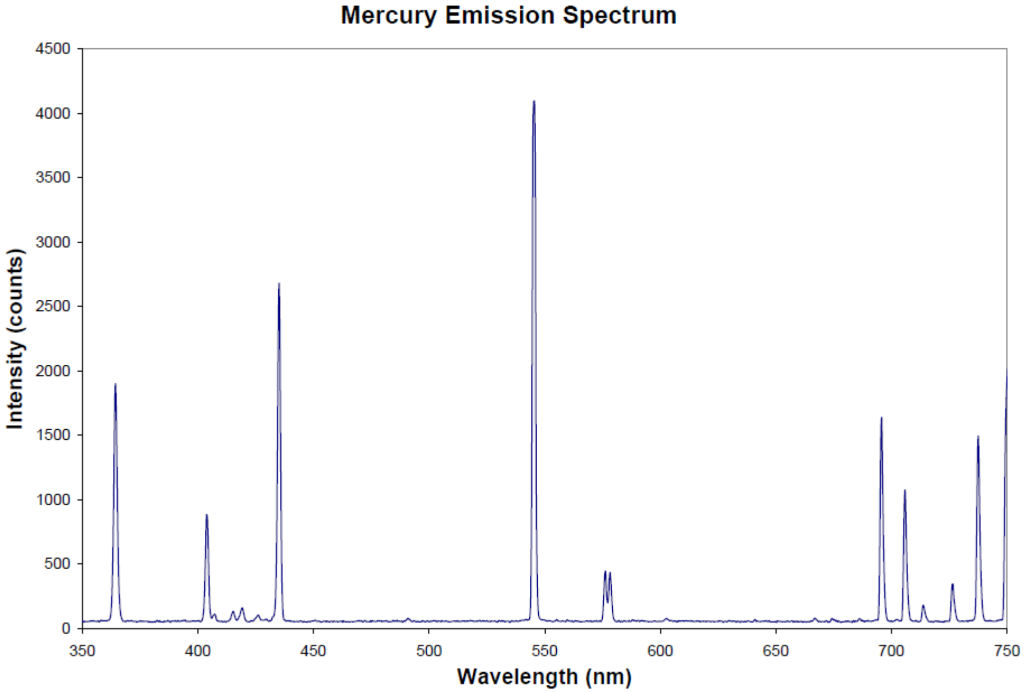
Mercury Lamp

Lamp



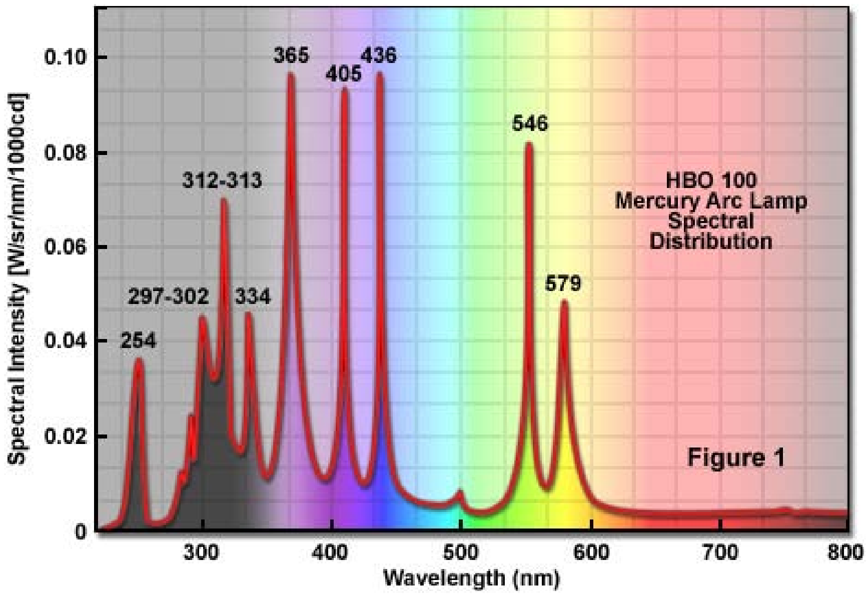
Spectrum

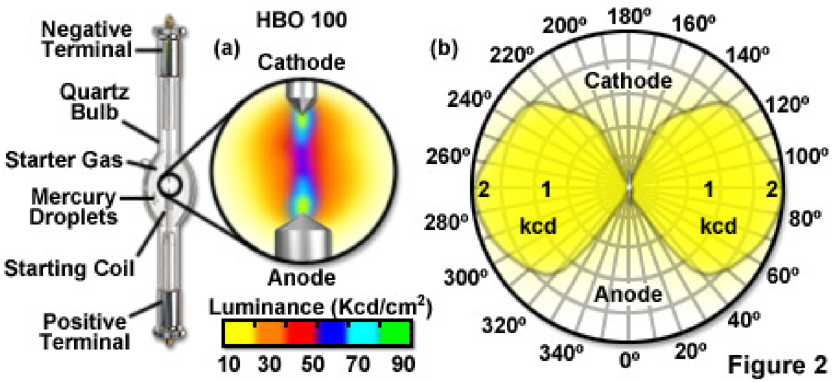




http://www1.assumption.edu/users/bniece/Spectra/Complete.html

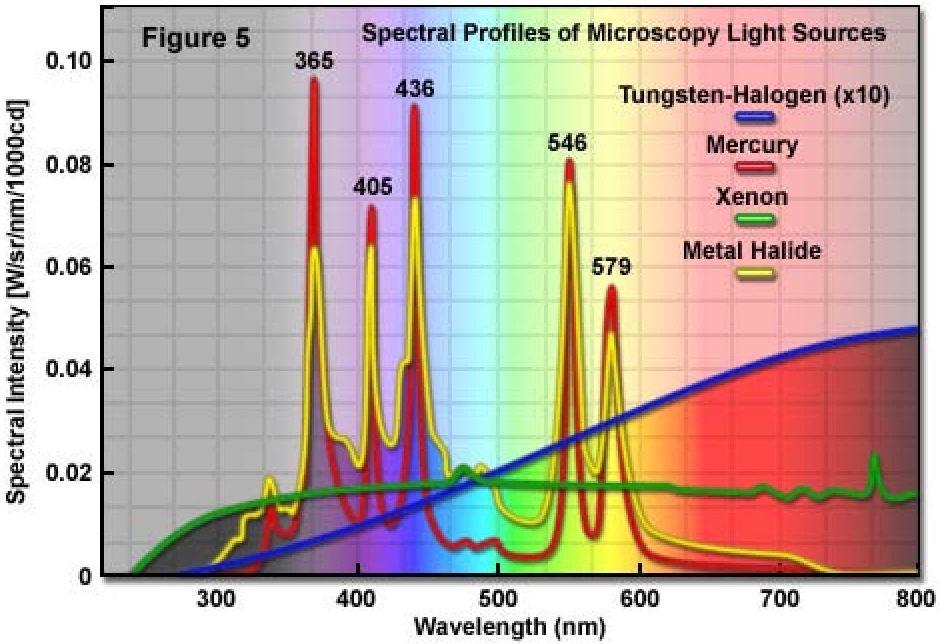
Mercury Arc Lamp





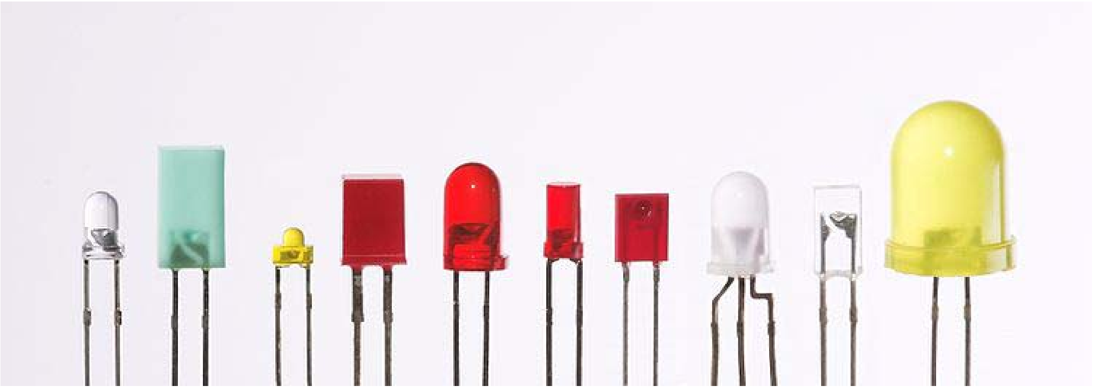
http://zeiss-campus.magnet.fsu.edu/articles/lightsources/mercuryarc.html

Spectral Profiles of Microscopy Light Sources

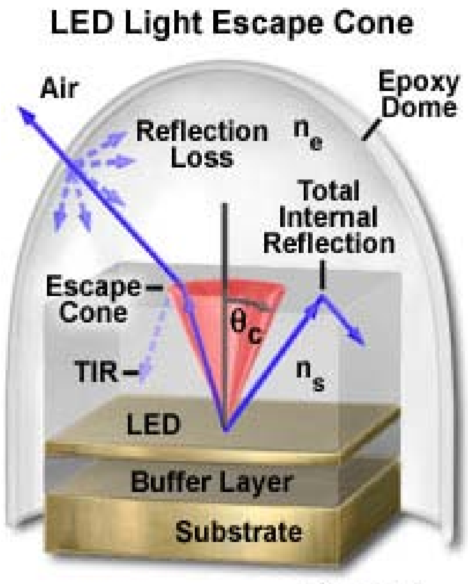


http://zeiss-campus.magnet.fsu.edu/articles/lightsources/lightsourcefundamentals.html

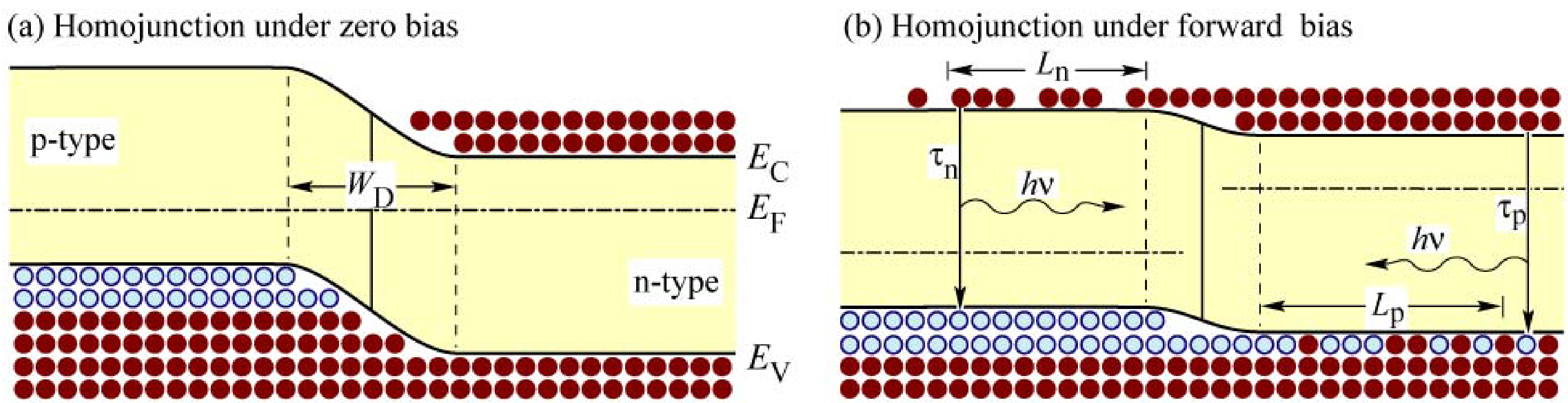
Light Emitting Diodes (LED)



https://en.wikipedia.org/wiki/Light-emitting_diode



Light Emitting Diodes (LED)



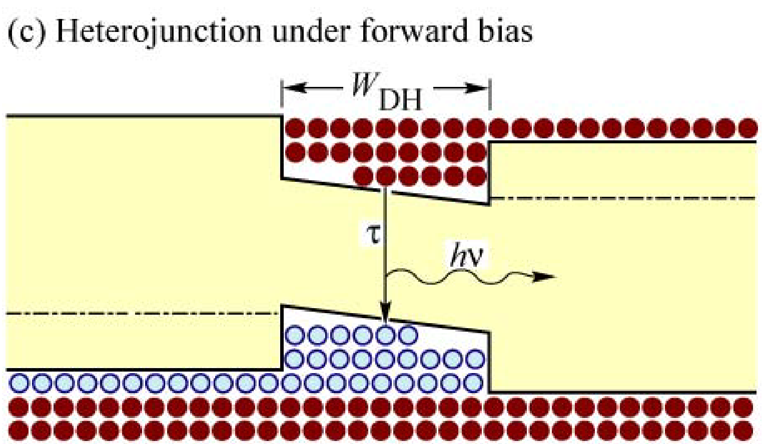


Fig. 4.6. P-n homojunction under (a) zero and (b) forward bias. (c) P-n heterojunction under forward bias. In homojunctions, carriers diffuse, on average, over the diffusion lengths L_n and L_p before recombining. In heterojunctions, carriers are confined by the heterojunction barriers.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Light Emitting Diodes (LED)

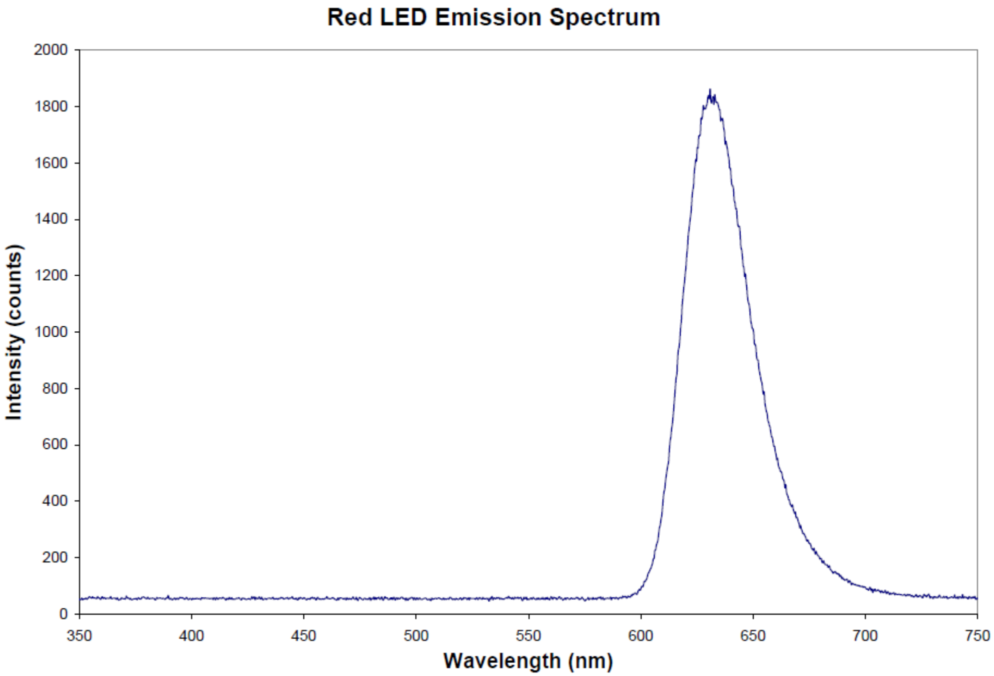
	Color	Wavelength (nm)	Voltage (V)	Semiconductor Material
	Infrared	λ > 760	ΔV < 1.9	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
	Red	610 < λ < 760	1.63 < ΔV < 2.03	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Orange	590 < λ < 610	2.03 < ΔV < 2.10	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Yellow	570 < λ < 590	2.10 < ΔV < 2.18	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Green	500 < λ < 570	1.9 < ΔV < 4.0	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP)Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
	Blue	450 < λ < 500	2.48 < ΔV < 3.7	Zinc selenide (ZnSe), Indium gallium nitride (InGaN), Silicon carbide (SiC) as substrate, Silicon (Si)
	Violet	400 < λ < 450	2.76 < ΔV < 4.0	Indium gallium nitride (InGaN)
	Purple	multiple types	2.48 < ΔV < 3.7	Dual blue/red LEDs,blue with red phosphor,or white with purple plastic
	Ultra-violet	λ < 400	3.1 < ΔV < 4.4	diamond (235 nm), Boron nitride (215 nm) , Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) (AlGaInN) — (to 210 nm)
	White	Broad spectrum	ΔV = 3.5	Blue/UV diode with yellow phosphor

https://www.google.gr/url?sa=t&rct=j&q=&esrc=s&source=web&cd=6&cad=rja&uact=8&ved=0CEIQFjAF&url=http%3A%2F%2Fwww.ohio.edu%2Fpeople%2Fstarzykj%2Fnetwork%2FClass%2FEE314%2FSlides%2FLecture7%2520Diode%2520Applications.ppt&ei=c5lRVf75C4SvygPH6oCgAg&usg=AFQjCNFQyZDlwCVczmli9PzGxYznYJA-yw

Red LED

Lamp

Spectrum

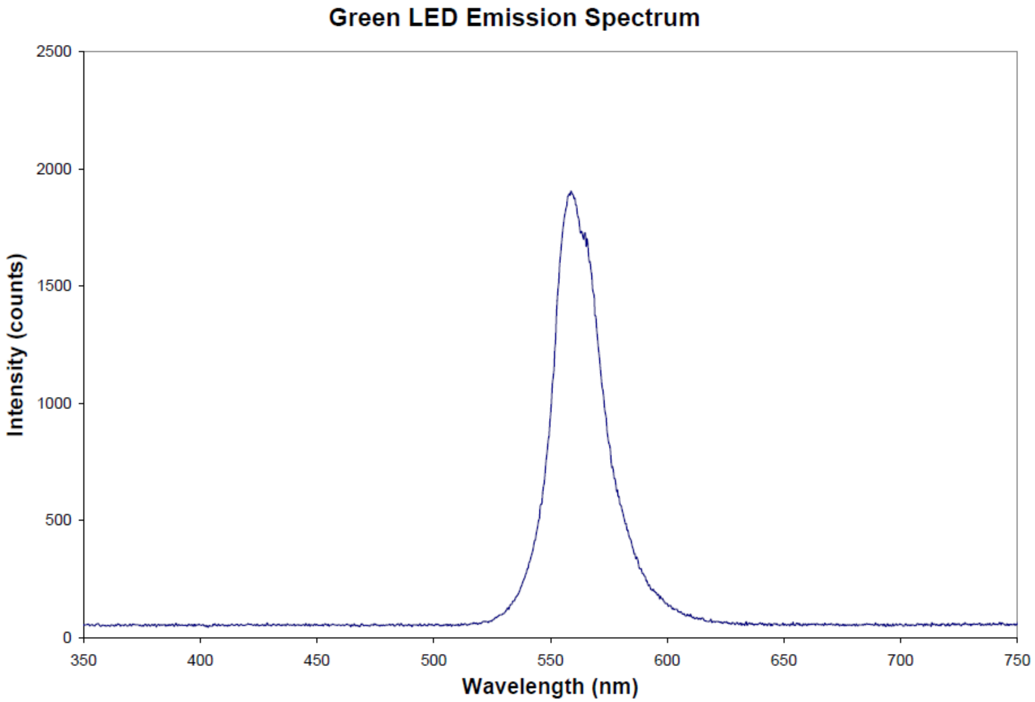


http://www1.assumption.edu/users/bniece/Spectra/Complete.html

Green LED

Lamp

Spectrum



http://www1.assumption.edu/users/bniece/Spectra/Complete.html

Light Emitting Diodes Spectra

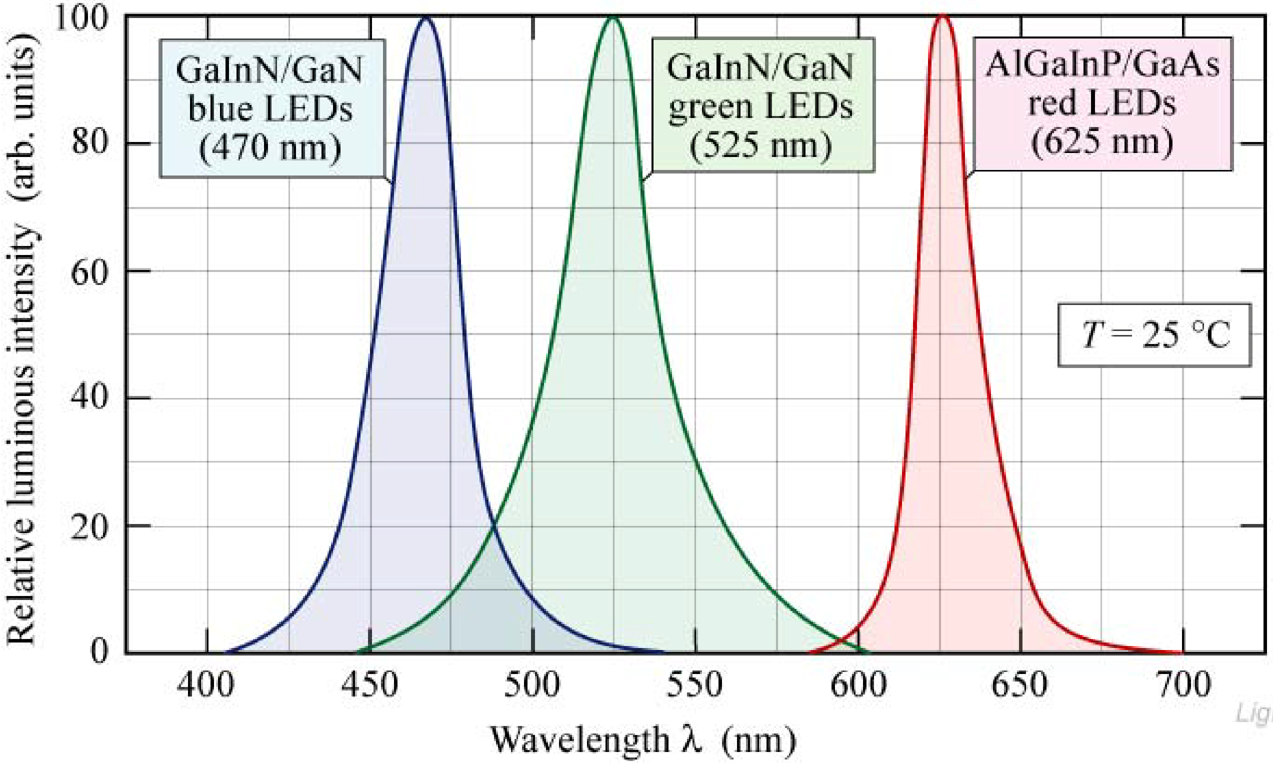


Fig. 12.16. Typical emission spectrum of GaInN/GaN blue, GaInN/GaN green, and AlGaInP/GaAs red LEDs at room temperature (after Toyoda Gosei Corp., 2000).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

https://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap12/F12-16%20RGB%20emission%20spectrum.jpg

Light Emitting Diodes Spectra

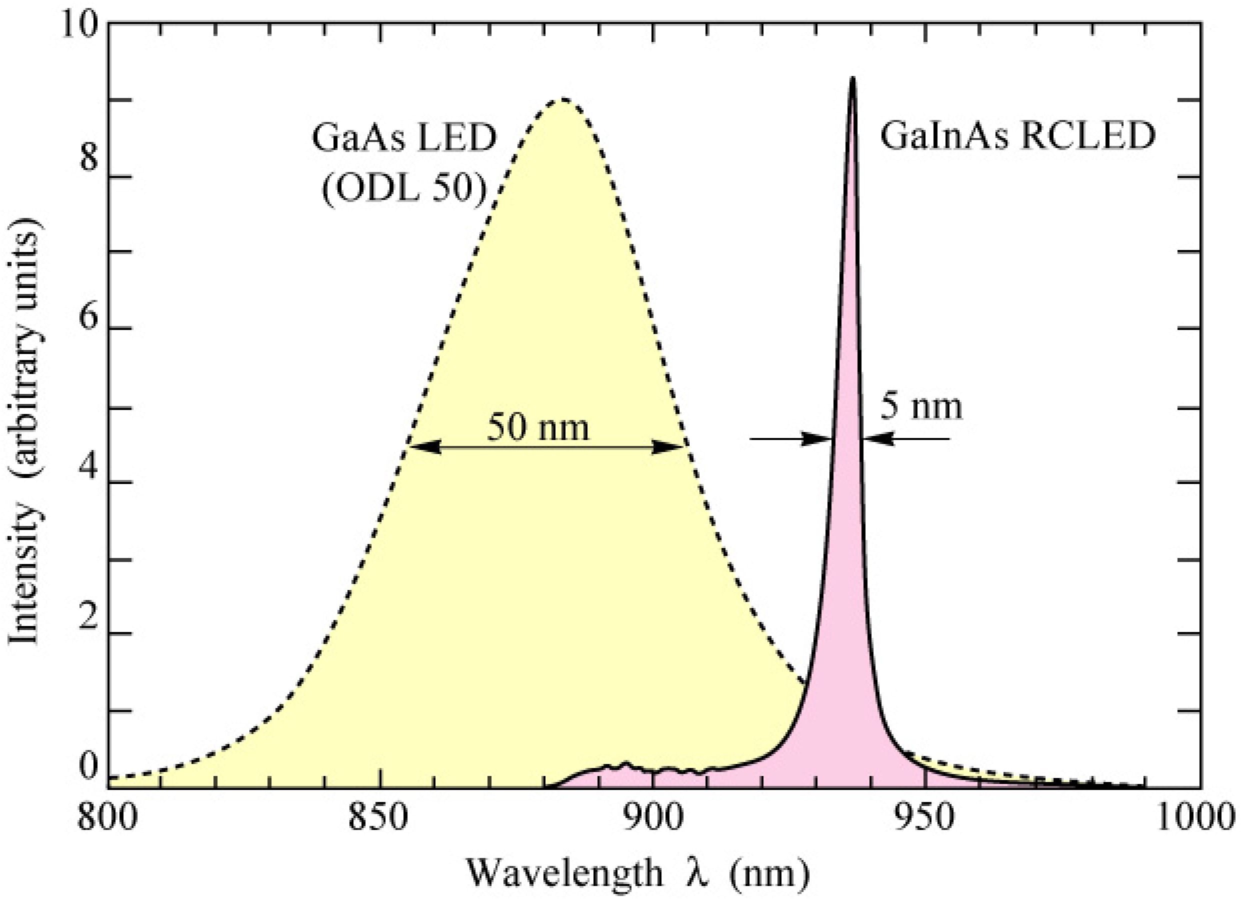
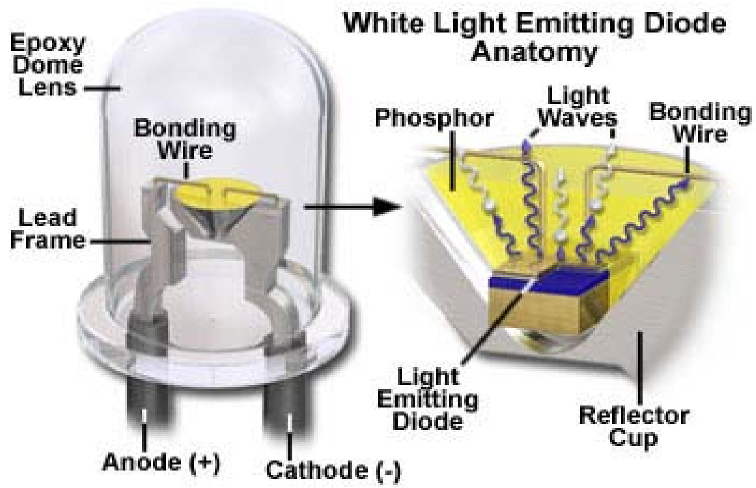


Fig. 15.6. Comparison of the emission spectra of a GaAs LED emitting at 870 nm (AT&T ODL 50 product) and a GaInAs RCLED emitting at 930 nm (after Hunt *et al.*, 1993).

From Schubert's Textbook "*Light Emitting Diodes*"

White LED Sources



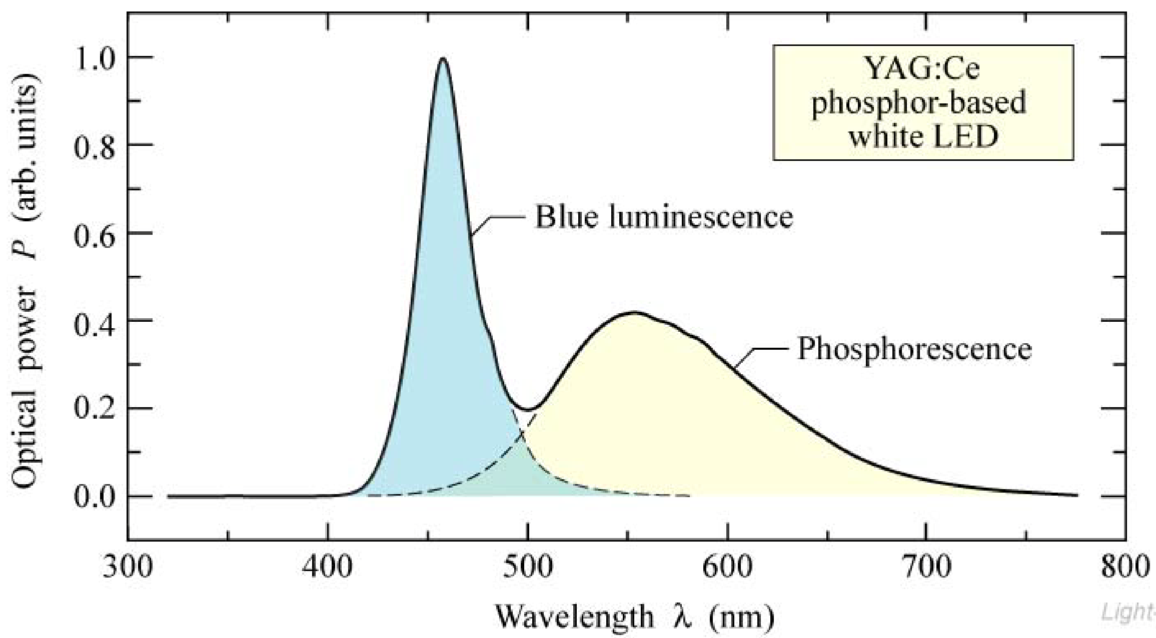


Fig. 21.8. Emission spectrum of a phophor-based white LED manufactured by Nichia Corporation (Anan, Tokushima, Japan).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

White LED Sources

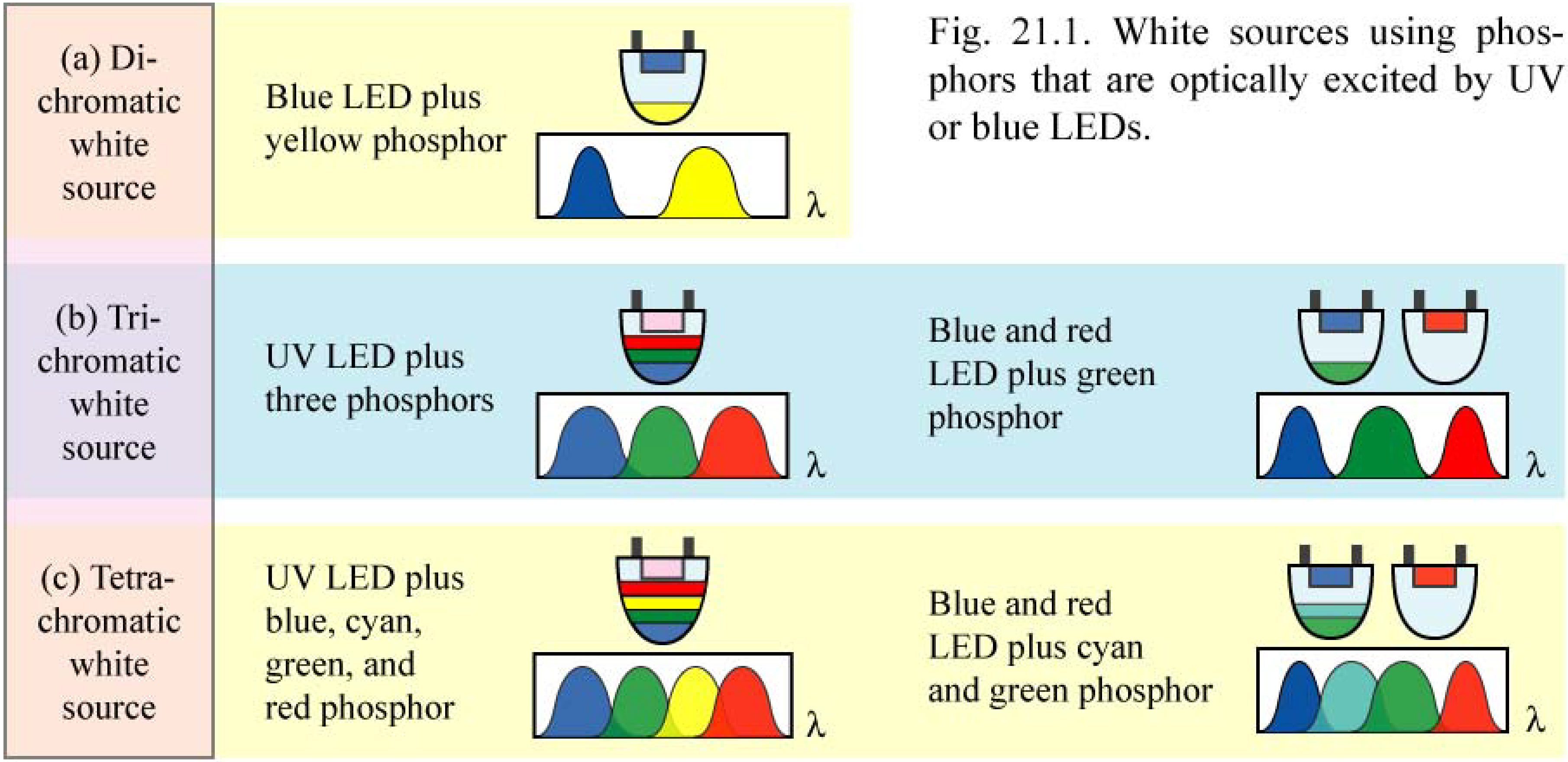
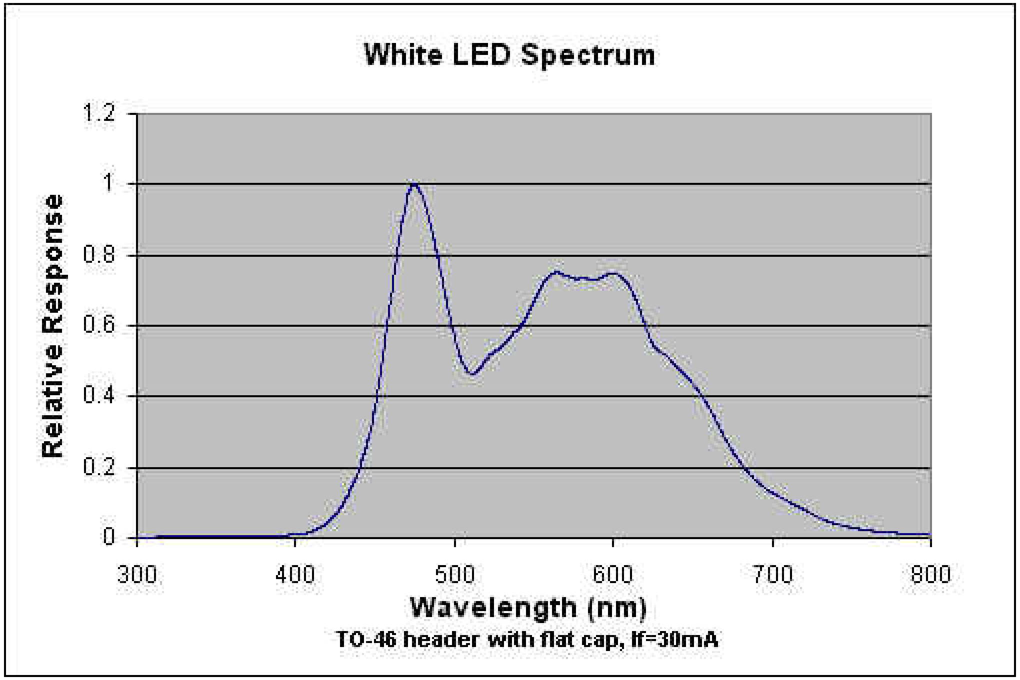
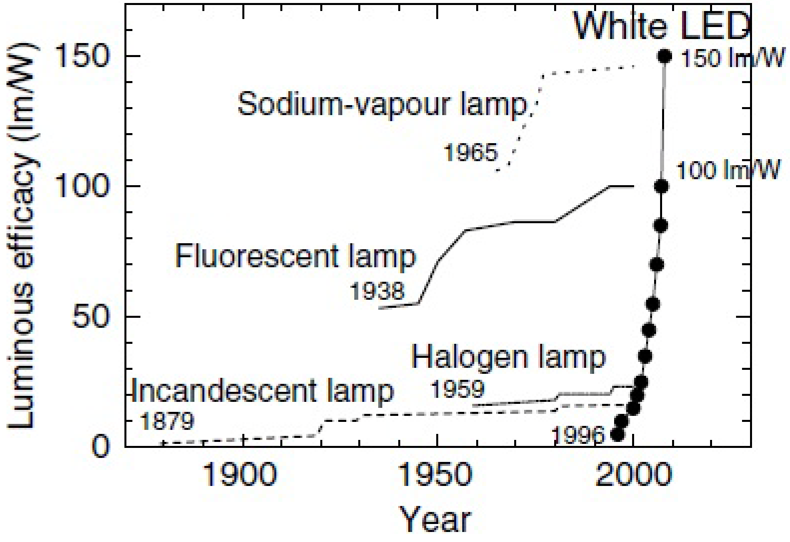


Fig. 21.1. White sources using phosphors that are optically excited by UV or blue LEDs.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

White LED Sources



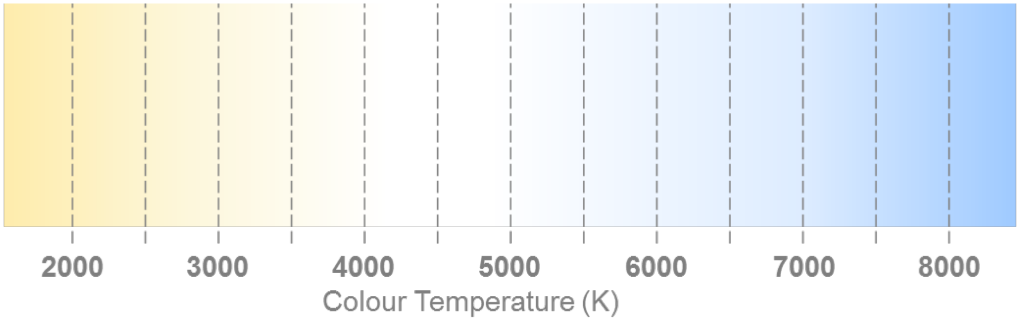


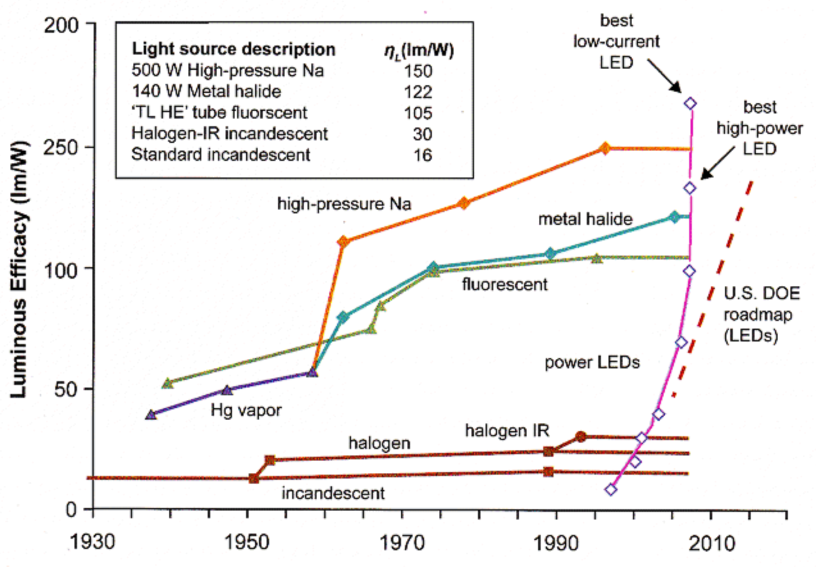
Warm White – 2,700 to 3,000 Kelvins
Neutral white – 3,000 to 4,000 Kelvins
Pure White – 4,000 to 5,000 Kelvins
Day White – 5,000 to 6,000 Kelvins
Cool White – 7,000 to 7,500 Kelvins

The history of luminous efficacy in different types of lighting shows the rapid improvements in white LEDs. The years in which the white light sources were developed are also shown.

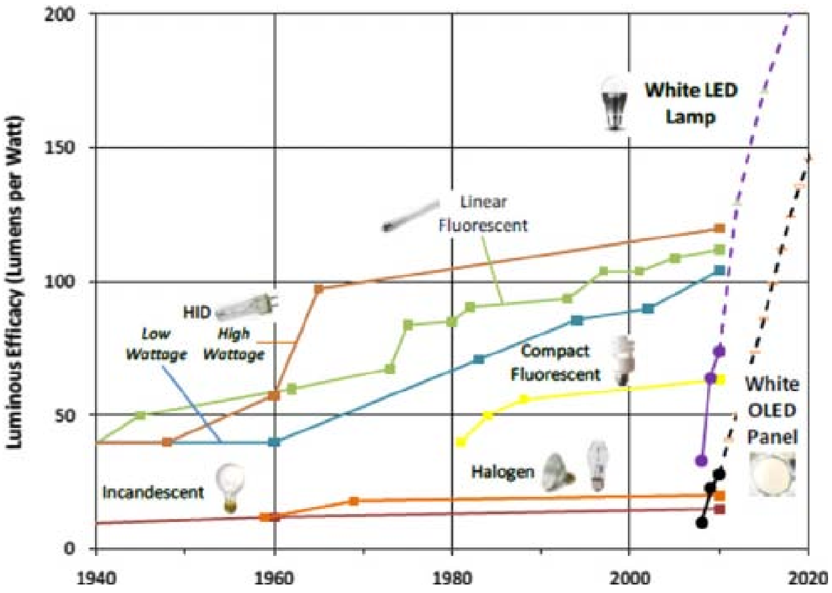
Yukio Narukawa, et al. "White light emitting diodes with super-high luminous efficacy." *J. Phys. D: Appl. Phys.* 43 (2010) 354002

White LED Sources





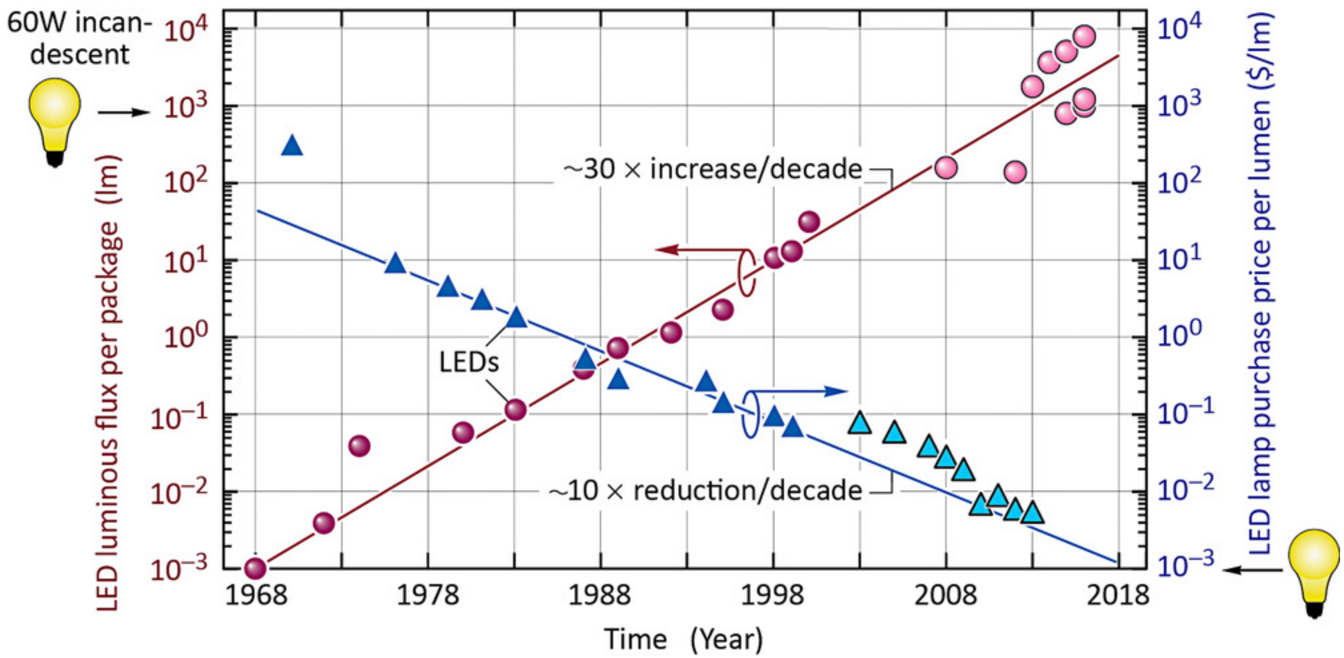
Light-emitting diodes versus conventional light sources. © 2007, IEEE



http://www.tf.uni-kiel.de/matwis/amat/semitech_en/kap_9/illustr/history_light_2.gif

https://www.researchgate.net/profile/Bruno_Santos6/publication/260998008/figure/fig6/AS:296670928621575@1447743269765/Fig-6-Historical-and-predicted-ef-fi-cacy-of-light-sources-Source-35.png

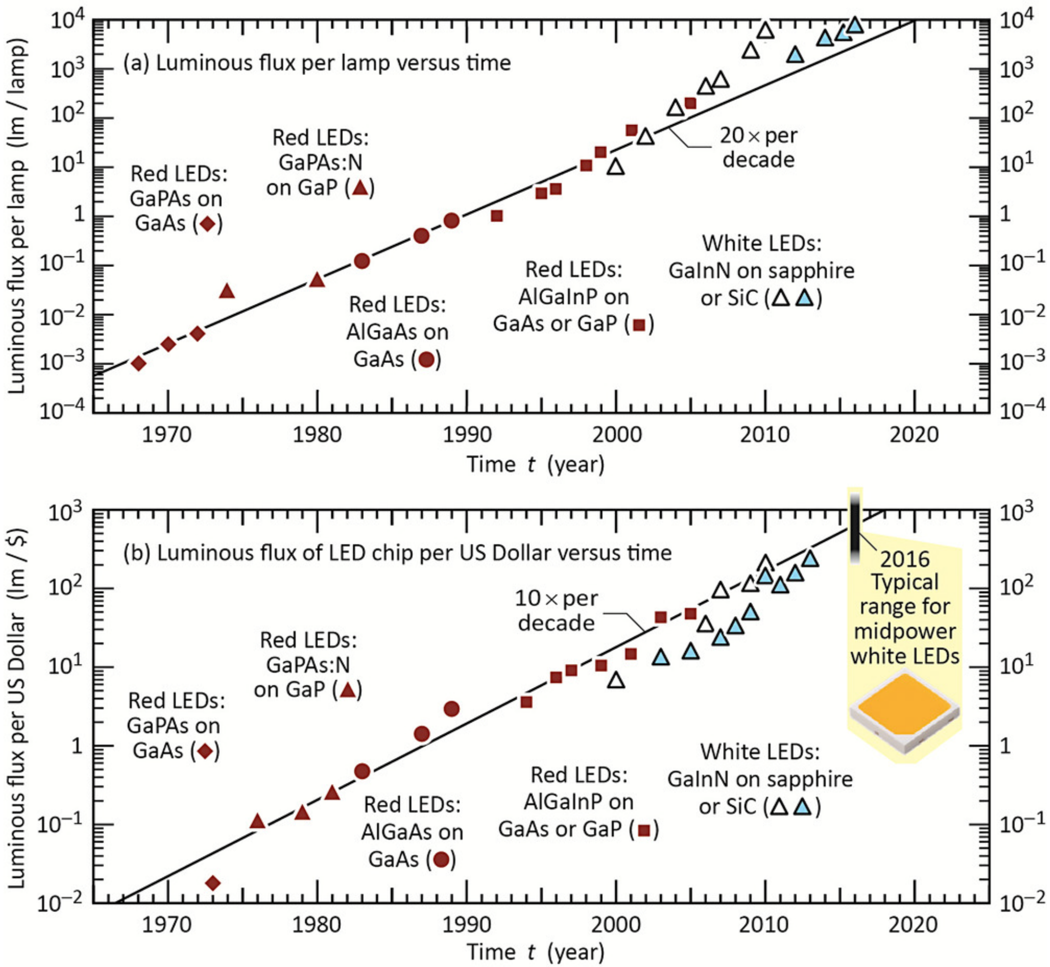
White LED Sources



LED luminous flux per package and LED lamp purchase price per lumen versus year. Also shown are the values for a 60 W incandescent tungsten-filament light bulb with a luminous efficiency of 17 lm/W and a luminous flux of 1000 lm with an approximate price of 1.00 US$

https://onlinelibrary.wiley.com/doi/10.1002/lpor.201600147

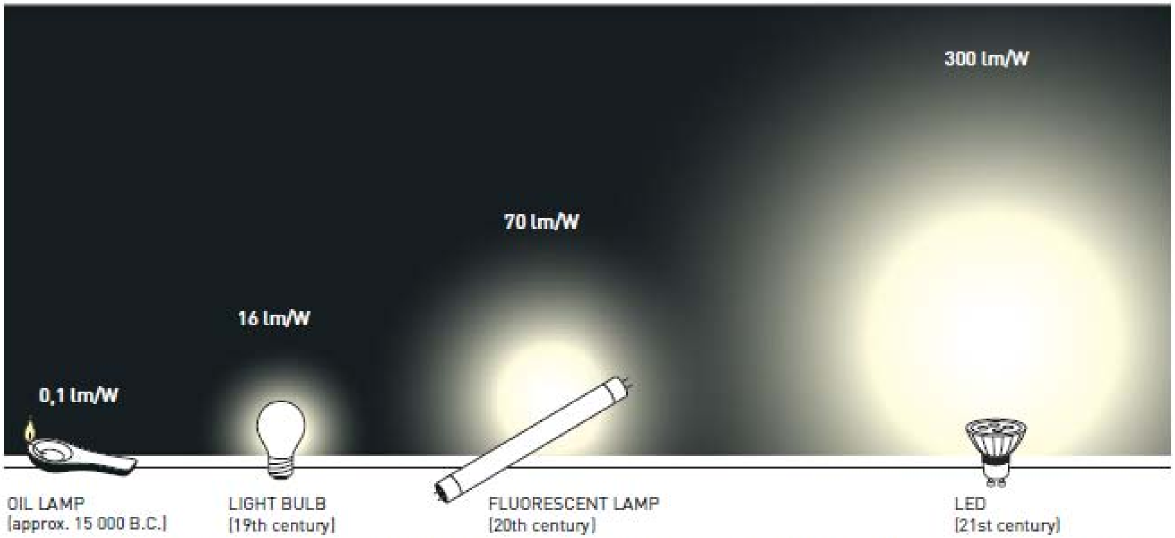
White LED Sources



https://onlinelibrary.wiley.com/doi/10.1002/lpor.201600147

Laser & Photonics Reviews, Volume: 11, Issue: 2, First published: 02 March 2017, DOI: (10.1002/lpor.201600147)

White LED Sources



LED lamps require less power to emit light than the older light sources. Efficiency is denoted in luminous flux (measured in lumen) per unit added power (measured in watt). As about one fourth of world electricity consumption is used for lighting purposes, the highly energy-efficient LED lamps contribute to saving the Earth's resources.

The Nobel Prize in Physics 2014

EFFICIENT BLUE LIGHT-EMITTING DIODES LEADING TO BRIGHT AND ENERGY-SAVING WHITE LIGHT SOURCES

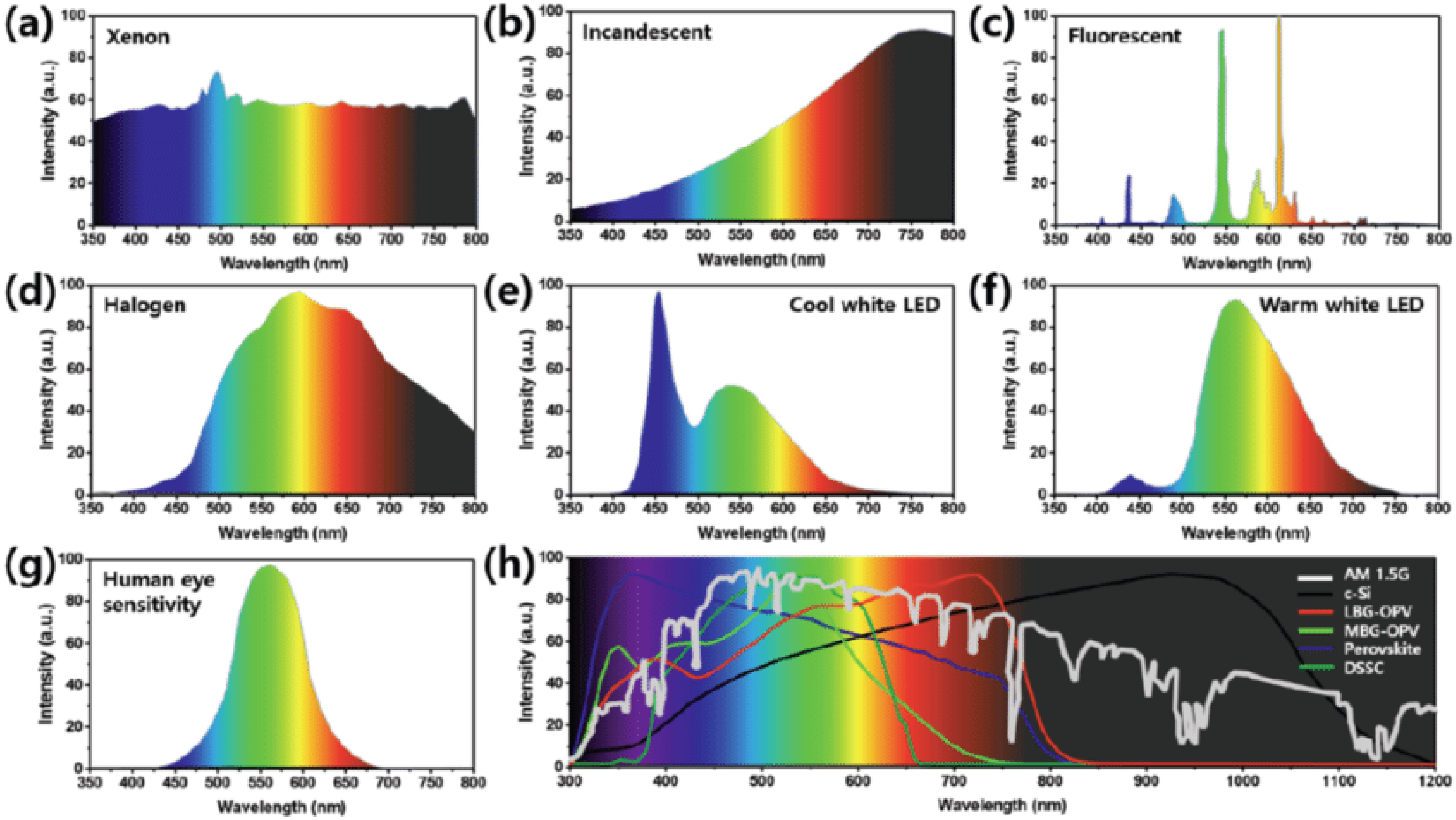
Isamu Akasaki

Hiroshi Amano

Shuji Nakamura

http://www.nobelprize.org/nobel_prizes/physics/laureates/2014/press.html

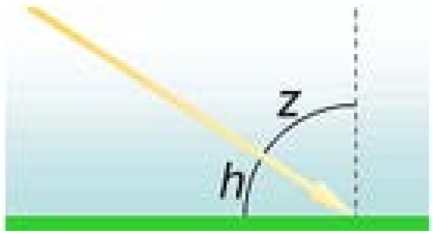
Comparison of Spectra of Various Sources



Spectra of the different indoor light sources. (a) Xenon lamp, (b) incandescent lamp, (c) fluorescent lamp, (d) halogen lamp, (e) cool white LED, (f) warm white LED, (g) human eye sensitivity spectrum, and (h) AM 1.5G spectrum overlaid with spectral response of various photovoltaic devices.

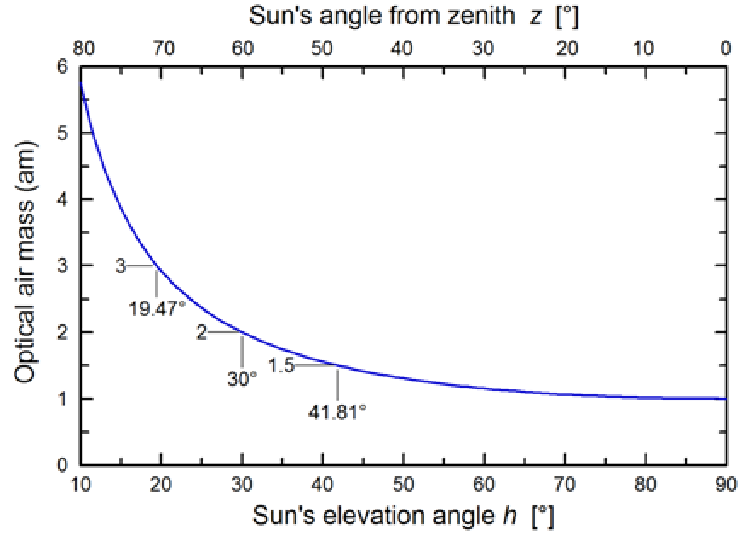
https://www.researchgate.net/profile/Muhammad-Jahandar/publication/330372622/figure/fig1/AS:722887845625858@1549361301844/Fig-2-Spectra-of-the-different-indoor-light-sources-a-Xenon-lamp-b-incandescent.png

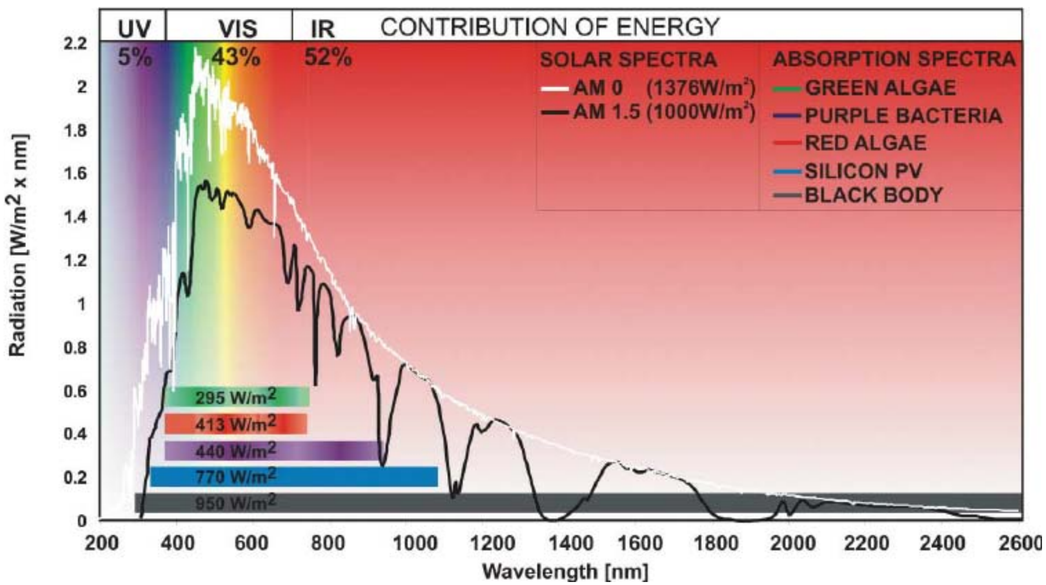
Atmospheric Mass Solar Spectrum



$$\text{am} = \frac{1}{\cos z} = \frac{1}{\sin h}$$

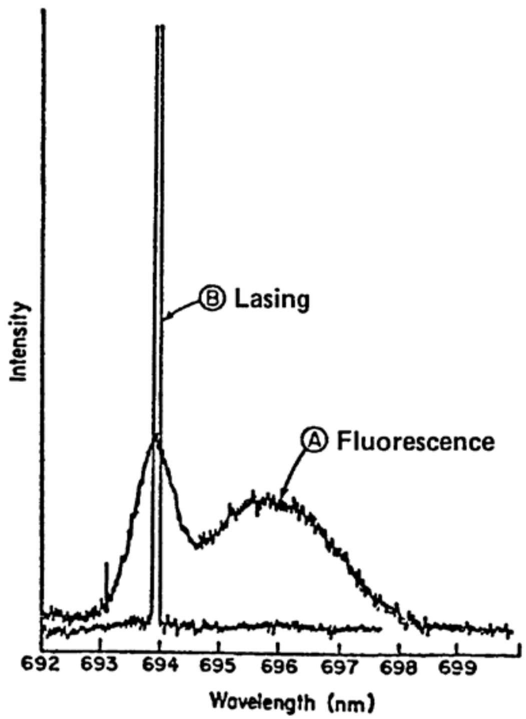
https://www2.pvlighthouse.com.au/resources/courses/altermatt/The%20Solar%20Spectrum/The%20air%20mass%20(AM).aspx





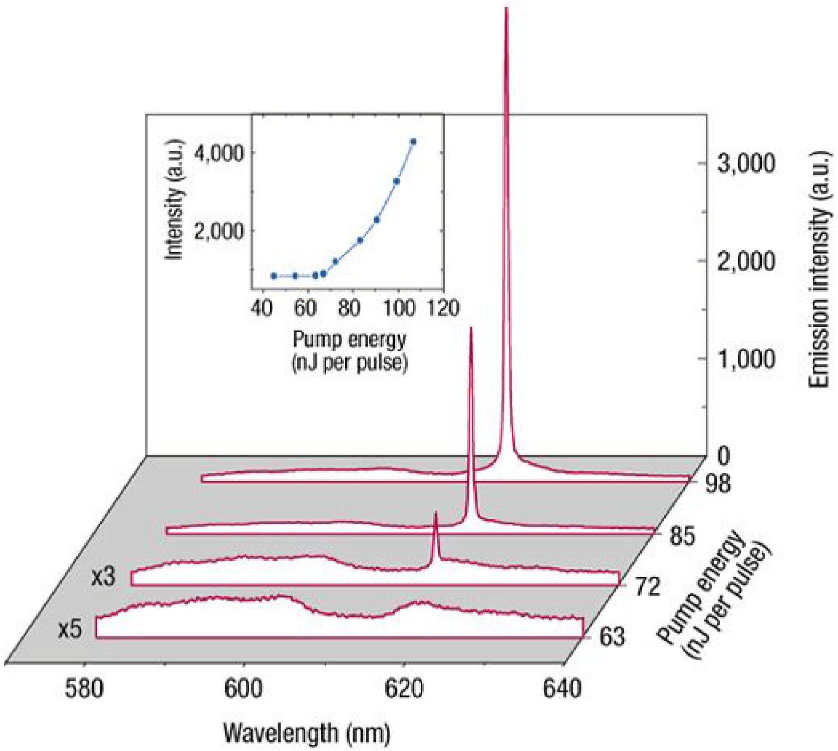
https://www.researchgate.net/publication/7461978/figure/fig1/AS:277667493498882@1443212497049/Solar-energy-distribution-and-capture-The-AM0-and-AM15-solar-irradiation-spectra-show.png

Fluorescence and Lasing



Light emitted from a ruby becomes more monochromatic as th pumping energy is increased. A) Fluorescence output below lasing threshold. B) Lasing above threshold.

J. R. Meyer-Arendt, Introduction to Classical and Modern Optics. New Jersey, Prentice Hall, 1995.

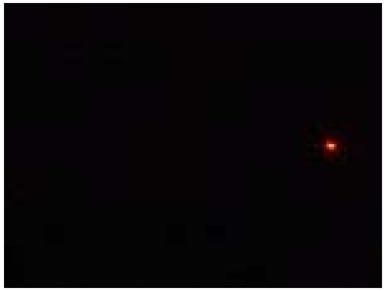


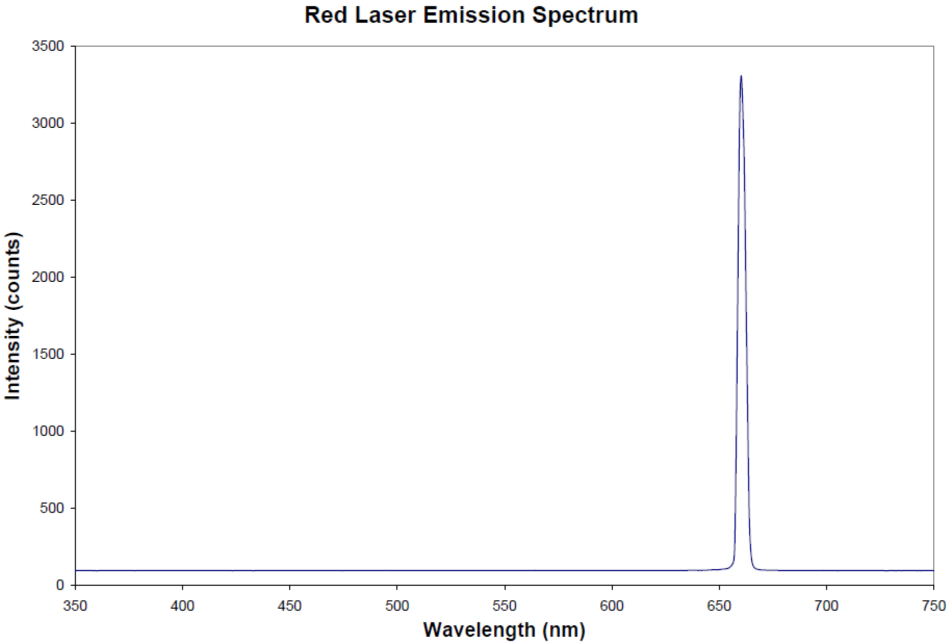
https://media.nature.com/lw926/nature-assets/nmat/journal/v1/n2/images/nmat727-f3.jpg

Red Laser Pointer

Lamp

Spectrum

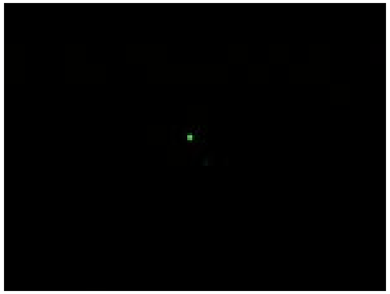




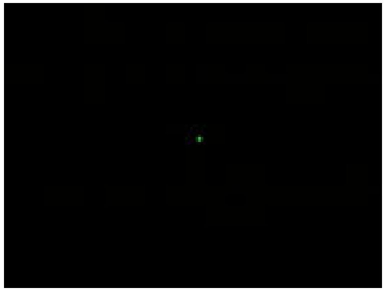
http://www1.assumption.edu/users/bniece/Spectra/Complete.html

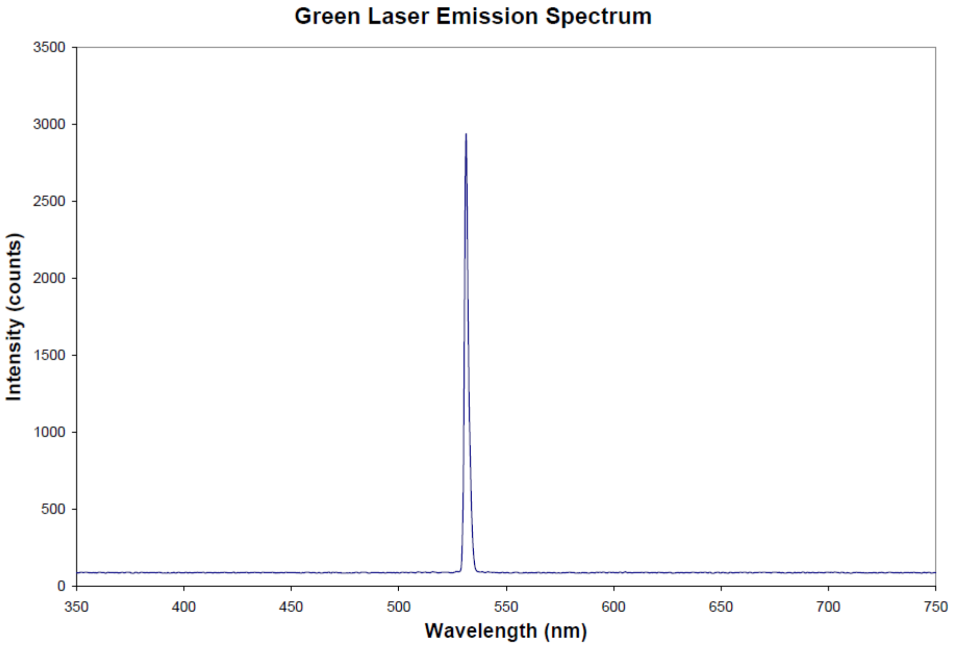
Green Laser Pointer

Lamp



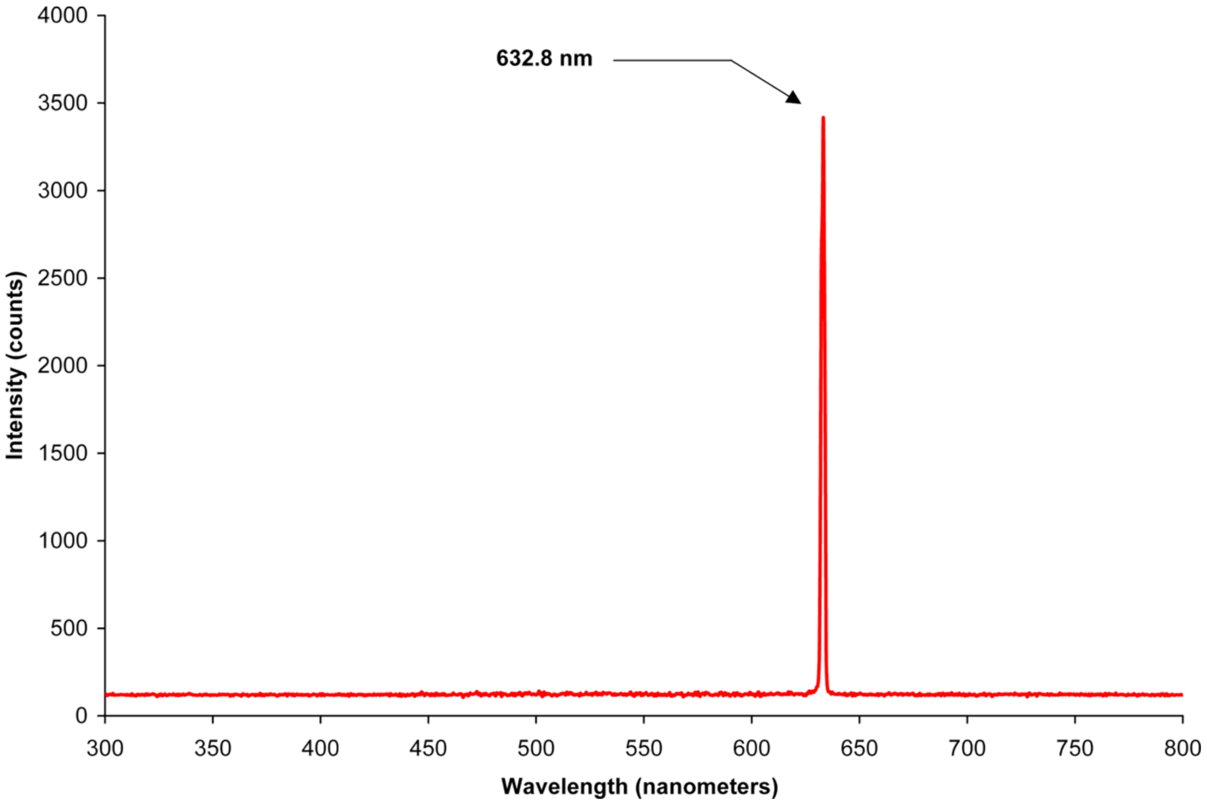
Spectrum





http://www1.assumption.edu/users/bniece/Spectra/Complete.html

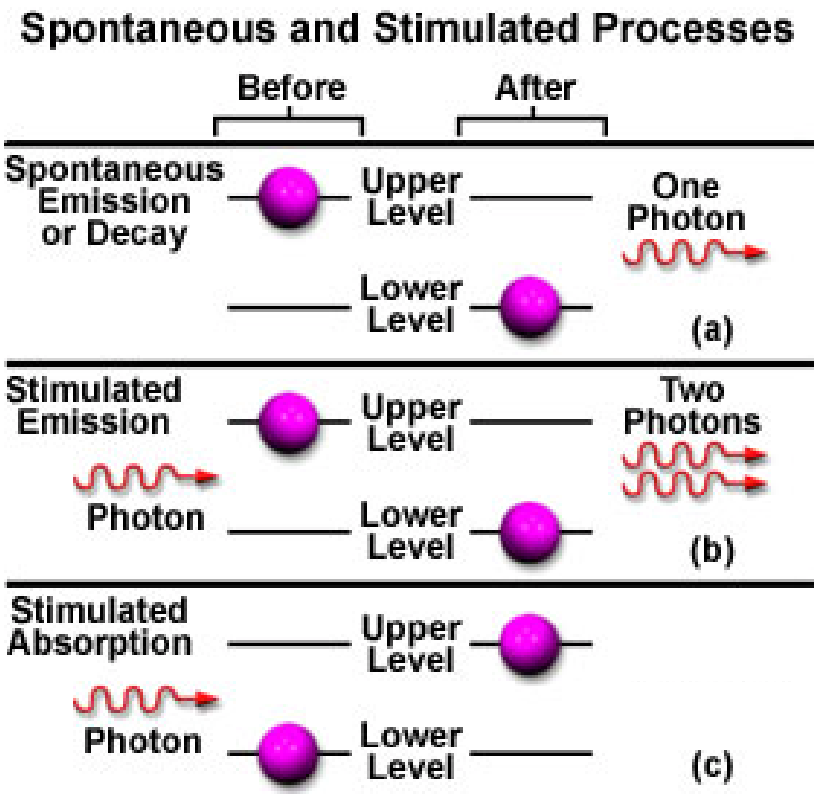
He-Ne Laser (red color)

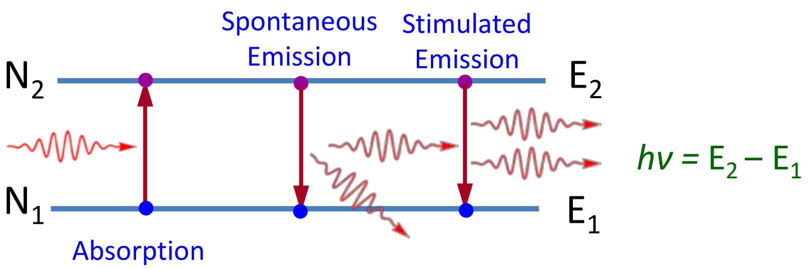


Spectrum of a He-Ne laser illustrating its very high spectral purity (limited by the measuring apparatus). The 0.002 nm bandwidth of the stimulated emission medium is well over **10,000** times narrower than the spectral width of a light-emitting diode with the bandwidth of a single longitudinal mode being much narrower still.

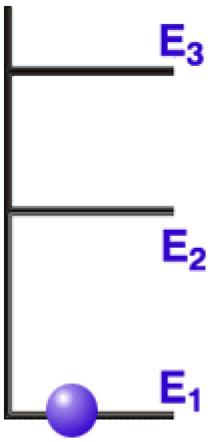
https://upload.wikimedia.org/wikipedia/commons/thumb/d/d7/Helium_neon_laser_spectrum.png/1280px-Helium_neon_laser_spectrum.png

Einstein's Radiative Processes

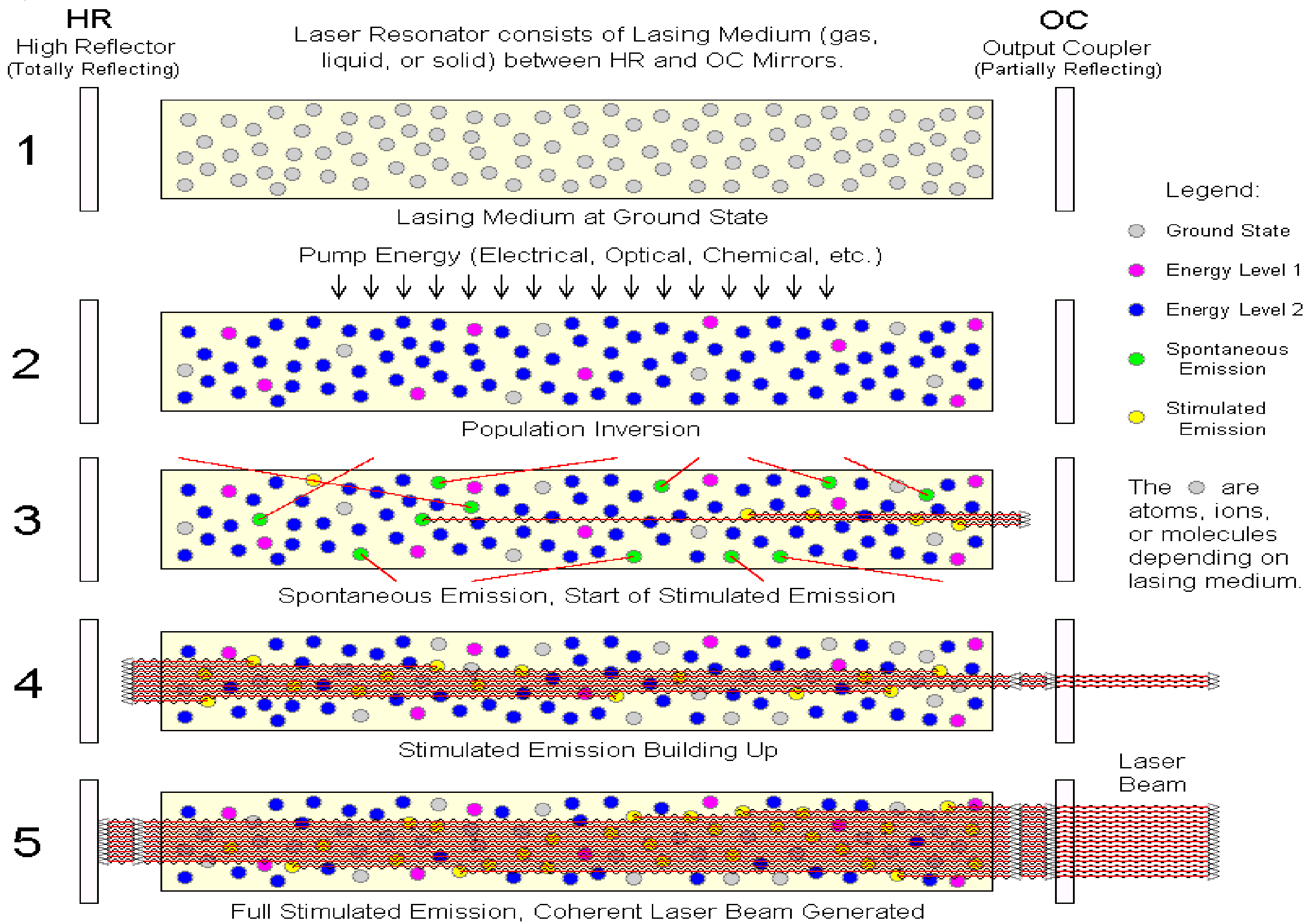




Stimulated Emission



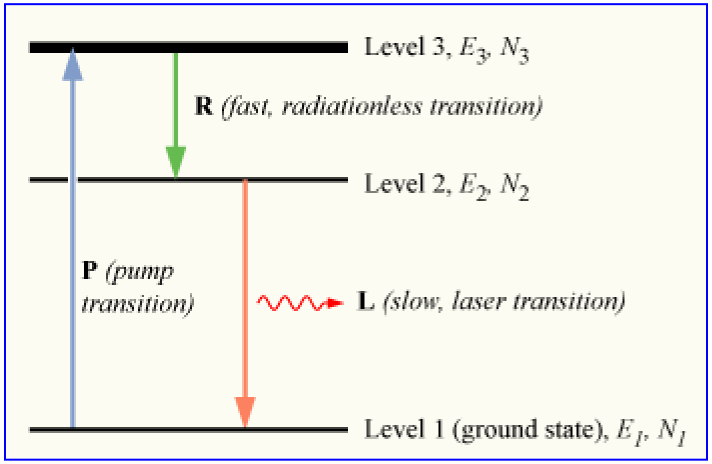
Laser Operation Basics



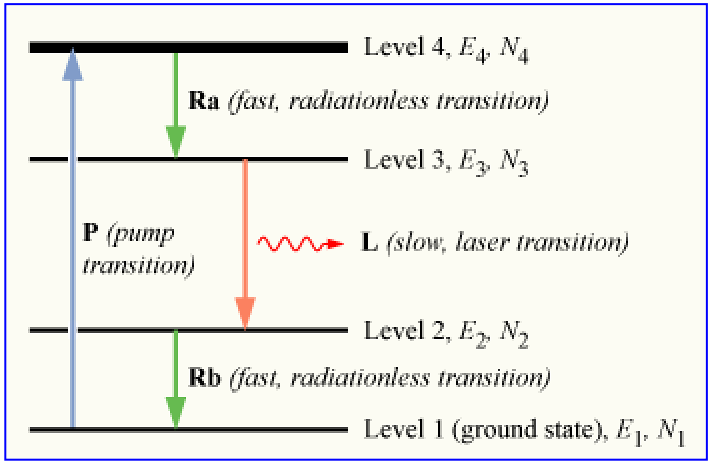
Basic Laser Operation

3-Level and 4-Level Lasers

3-Level

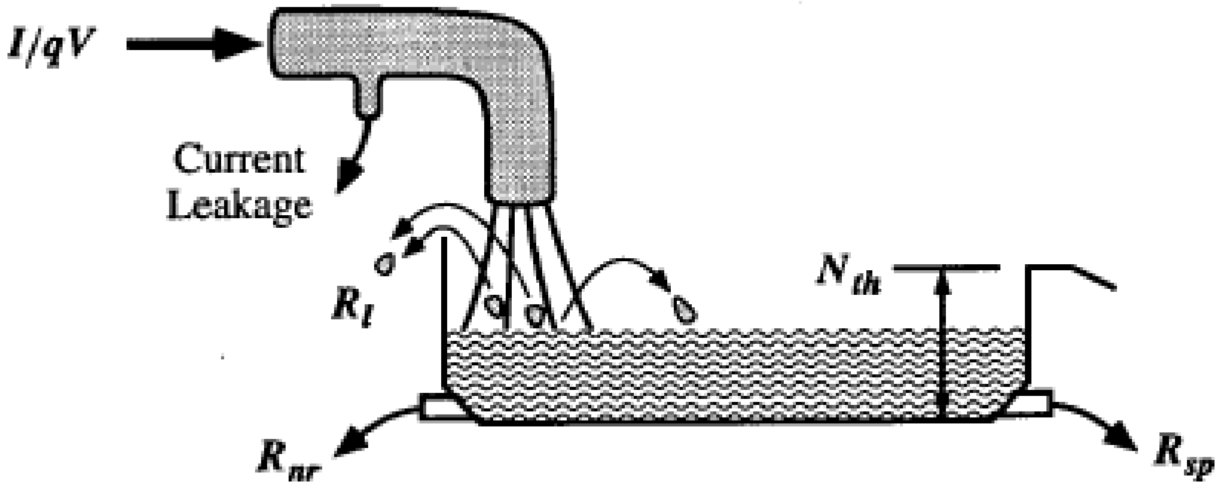


4-Level

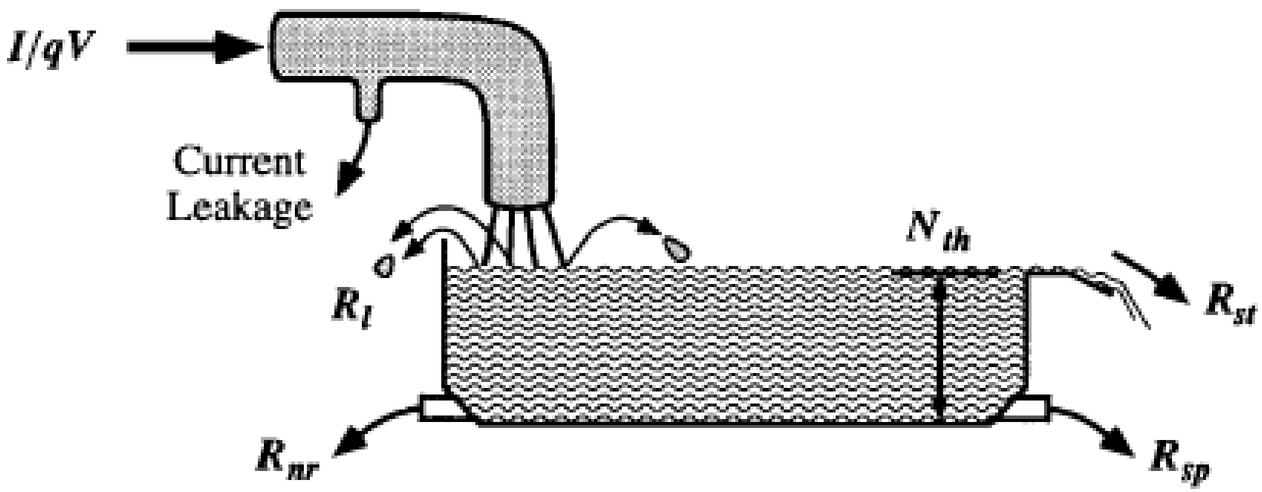


http://en.wikipedia.org/wiki/Population_inversion

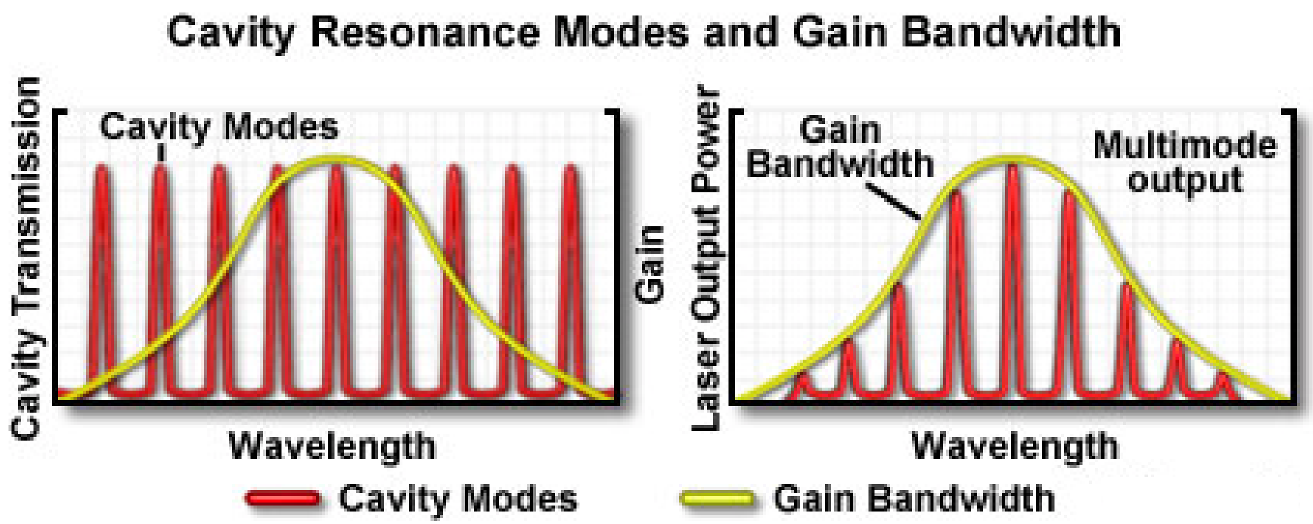
Laser Below Threshold



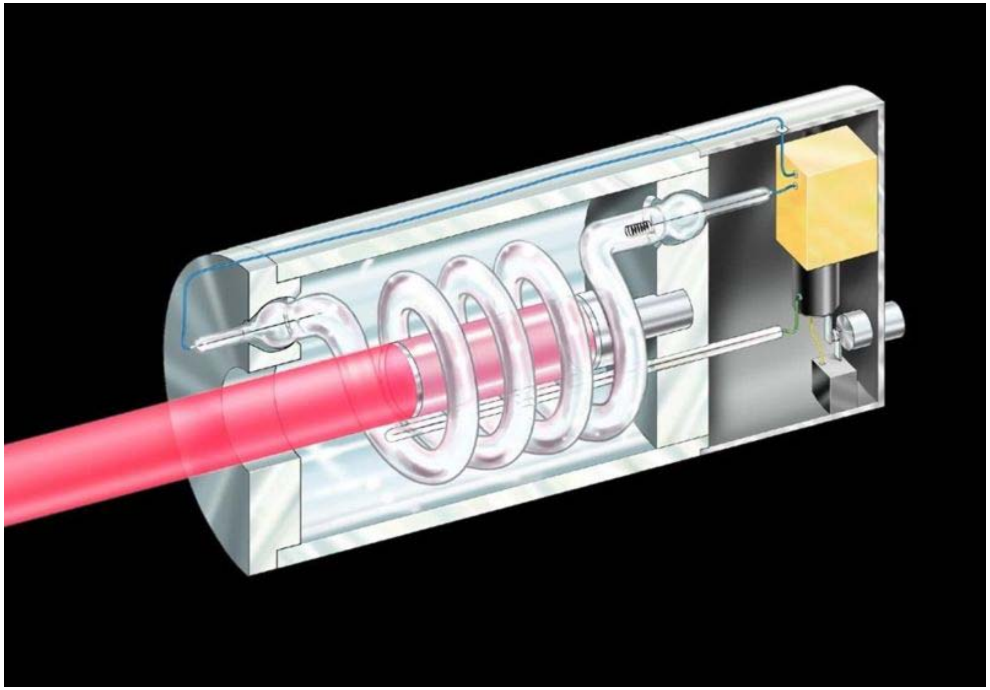
Laser Above Threshold



Coldren and Corzine, Diode Lasers & Photonic Integrated Circuits, J. Wiley (1995)

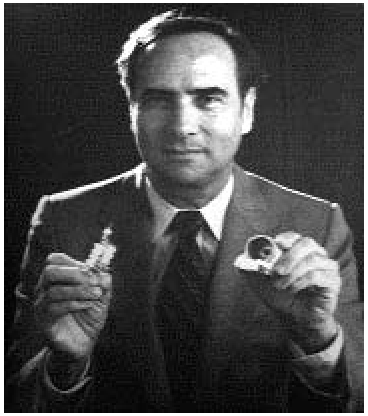

Cavity Resonance Modes and Gain Bandwidth
Cavity Transmission
Cavity Modes
Wavelength
Gain
Laser Output Power
Gain
Bandwidth
Multimode
output
Wavelength
Cavity Modes
Gain Bandwidth

First Demonstrated Laser Operation (Ruby laser – Mainman -1960)



Actual Picture of Laser Lamp and Ruby Rod

Theodore H. Mainman (1927-2007)



Common Laser Types

LASERS	TYPE	WAVELENGTH	COLOR	TYPICAL OPERATION
He–Cd	gas	441.6nm	violet	c. w.
Ar ion	gas	488.0nm	violet	c. w.
		514.5nm	green	c. w.
He–Ne	gas	632.8nm	red	c. w.
ruby	solid	693.4nm	red	pulsed
GaAs	solid	840.0nm	i. r.	c. w. pulsed
Nd:YAG	solid	1.06μm	i. r.	pulsed
Nd:glass	solid	1.06μm	i. r.	pulsed
CO_2	gas	10.6μm	i. r.	c. w. pulsed

Common Gas Lasers

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Argon laser	454.6 nm, 488.0 nm, 514.5 nm (351 nm, 363.8, 457.9 nm, 465.8 nm, 476.5 nm, 472.7 nm, 528.7 nm, also frequency doubled to provide 244 nm, 257 nm)	Electrical discharge	Retinal phototherapy (for diabetes), lithography, confocal microscopy, spectroscopypumping other lasers.
Carbon dioxide laser	10.6 μm, (9.4 μm)	Transverse (high power) or longitudinal (low power) electrical discharge	Material processing (cutting, welding, etc.), surgery, dental laser, military lasers.
Carbon monoxide laser	2.6 to 4 μm, 4.8 to 8.3 μm	Electrical discharge	Material processing (engraving, welding, etc.), photoacoustic spectroscopy.
Excimer laser	193 nm (ArF), 248 nm (KrF), 308 nm (XeCl), 353 nm (XeF)	Excimer recombination via electrical discharge	Ultraviolet lithography for semiconductor manufacturing, laser surgery, LASIK.
Helium–neon laser	632.8 nm (543.5 nm, 593.9 nm, 611.8 nm, 1.1523 μm, 1.52 μm, 3.3913 μm)	Electrical discharge	Interferometry, holography, spectroscopy, barcode scanning, alignment, optical demonstrations.
Krypton laser	416 nm, 530.9 nm, 568.2 nm, 647.1 nm, 676.4 nm, 752.5 nm, 799.3 nm	Electrical discharge	Scientific research, mixed with argon to create "white-light" lasers, light shows.
Nitrogen laser	337.1 nm	Electrical discharge	Pumping of dye lasers, measuring air pollution, scientific research. Nitrogen lasers can operate superradiantly (without a resonator cavity). Amateur laser construction. See TEA laser
Xenon ion laser	Many lines throughout visible spectrum extending into the UV and IR.	Electrical discharge	Scientific research.

https://en.wikipedia.org/wiki/List_of_laser_types

Some Chemical Lasers

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Hydrogen fluoride laser	2.7 to 2.9 µm for Hydrogen fluoride(<80% Atmospheric transmittance)	Chemical reaction in a burning jet of ethylene and nitrogen trifluoride (NF_3)	Used in research for laser weaponry, operated in continuous wave mode, can have power in the megawatt range.
Deuterium fluoride laser	~3800 nm (3.6 to 4.2 µm) (~90% Atm. transmittance)	chemical reaction	US military laser prototypes.
COIL (Chemicaloxygen–iodinelaser)	1.315 µm (<70% Atmospheric transmittance)	Chemical reaction in a jet of singlet delta oxygen and iodine	Military lasers, scientific and materials research. Can operate in continuous wave mode, with power in the megawatt range.
Agil (All gas-phase iodine laser)	1.315 µm (<70% Atmospheric transmittance)	Chemical reaction of chlorine atoms with gaseous hydrazoic acid, resulting in excited molecules of nitrogen chloride, which then pass their energy to the iodine atoms.	Scientific, weaponry, aerospace.

Dye (Liquid) Lasers

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Dye lasers	390-435 nm (stilbene), 460-515 nm (coumarin 102), 570-640 nm (rhodamine 6G), many others	Other laser, flashlamp	Research, laser medicine,[2] spectroscopy, birthmark removal, isotope separation. The tuning range of the laser depends on which dye is used.

https://en.wikipedia.org/wiki/List_of_laser_types

Some Metal-Vapor Lasers

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Helium–cadmium (HeCd) metal-vapor laser	325 nm, 441.563 nm	Electrical discharge in metal vapor mixed with helium buffer gas.	Printing and typesetting applications, fluorescence excitation examination (i.e. in U.S. paper currency printing), scientific research.
Helium–mercury (HeHg) metal-vapor laser	567 nm, 615 nm		Rare, scientific research, amateur laser construction.
Helium–selenium (HeSe) metal-vapor laser	up to 24 wavelengths between red and UV		Rare, scientific research, amateur laser construction.
Helium–silver (HeAg) metal-vapor laser[3]	224.3 nm		Scientific research
Strontium Vapor Laser	430.5 nm		Scientific research
Neon–copper (NeCu) metal-vapor laser[3]	248.6 nm	Electrical discharge in metal vapor mixed with neon buffer gas.	Scientific research
Copper vapor laser	510.6 nm, 578.2 nm	Electrical discharge	Dermatological uses, high speed photography, pump for dye lasers.
Gold vapor laser	627 nm		Rare, dermatological and photodynamic therapy uses.[4]
Manganese (Mn/MnCl2) vapor laser	534.1 nm	Pulsed electric discharge	*Optics Communications*. ***51*** *(6): 387. 1987.* Missing or empty |title= (help)

https://en.wikipedia.org/wiki/List_of_laser_types

Some Solid-State Lasers

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Ruby laser	694.3 nm	Flashlamp	Holography, tattoo removal. The first type of visible light laser invented; May 1960.
Nd:YAG laser	1.064 μm, (1.32 μm)	Flashlamp, laser diode	Material processing, rangefinding, laser target designation, surgery, tattoo removal, hair removal, research, pumping other lasers (combined with frequency doubling to produce a green 532 nm beam). One of the most common high power lasers. Usually pulsed (down to fractions of a nanosecond), dental laser
NdCrYAG laser	1.064 μm, (1.32 μm)	solar radiation	Experimental production of nanopowders.[5]
Er:YAG laser	2.94 μm	Flashlamp, laser diode	Periodontal scaling, Dental laser, Skin Resurfacing
Neodymium YLF (Nd:YLF) solid-state laser	1.047 and 1.053 μm	Flashlamp, laser diode	Mostly used for pulsed pumping of certain types of pulsed Ti:sapphire lasers, combined with frequency doubling.
Neodymium doped Yttrium orthovanadate ($Nd:YVO_4$) laser	1.064 μm	laser diode	Mostly used for continuous pumping of mode-locked Ti:sapphire or dye lasers, in combination with frequency doubling. Also used pulsed for marking and micromachining. A frequency doubled $nd:YVO_4$ laser is also the normal way of making a green laser pointer.
Neodymium doped yttrium calcium oxoborateNd:$YCa_4O(BO_3)_3$ or simply Nd:YCOB	~1.060 μm (~530 nm at second harmonic)	laser diode	Nd:YCOB is a so-called "self-frequency doubling" or SFD laser material which is both capable of lasing and which has nonlinear characteristics suitable for second harmonic generation. Such materials have the potential to simplify the design of high brightness green lasers.
Neodymium glass(Nd:Glass) laser	~1.062 μm (Silicate glasses), ~1.054 μm (Phosphate glasses)	Flashlamp, laser diode	Used in extremely high power (terawatt scale), high energy (megajoules) multiple beam systems for inertial confinement fusion. Nd:Glass lasers are usually frequency tripled to the third harmonic at 351 nm in laser fusion devices.
Titanium sapphire(Ti:sapphire) laser	650-1100 nm	Other laser	Spectroscopy, LIDAR, research. This material is often used in highly-tunable mode-locked infrared lasers to produce ultrashort pulses and in amplifier lasers to produce ultrashort and ultra-intense pulses.
Thulium YAG (Tm:YAG) laser	2.0 μm	Laser diode	LIDAR.
Ytterbium YAG (Yb:YAG) laser	1.03 μm	Laser diode, flashlamp	Optical refrigeration, materials processing, ultrashort pulse research, multiphoton microscopy, LIDAR.

Some Solid-State Lasers

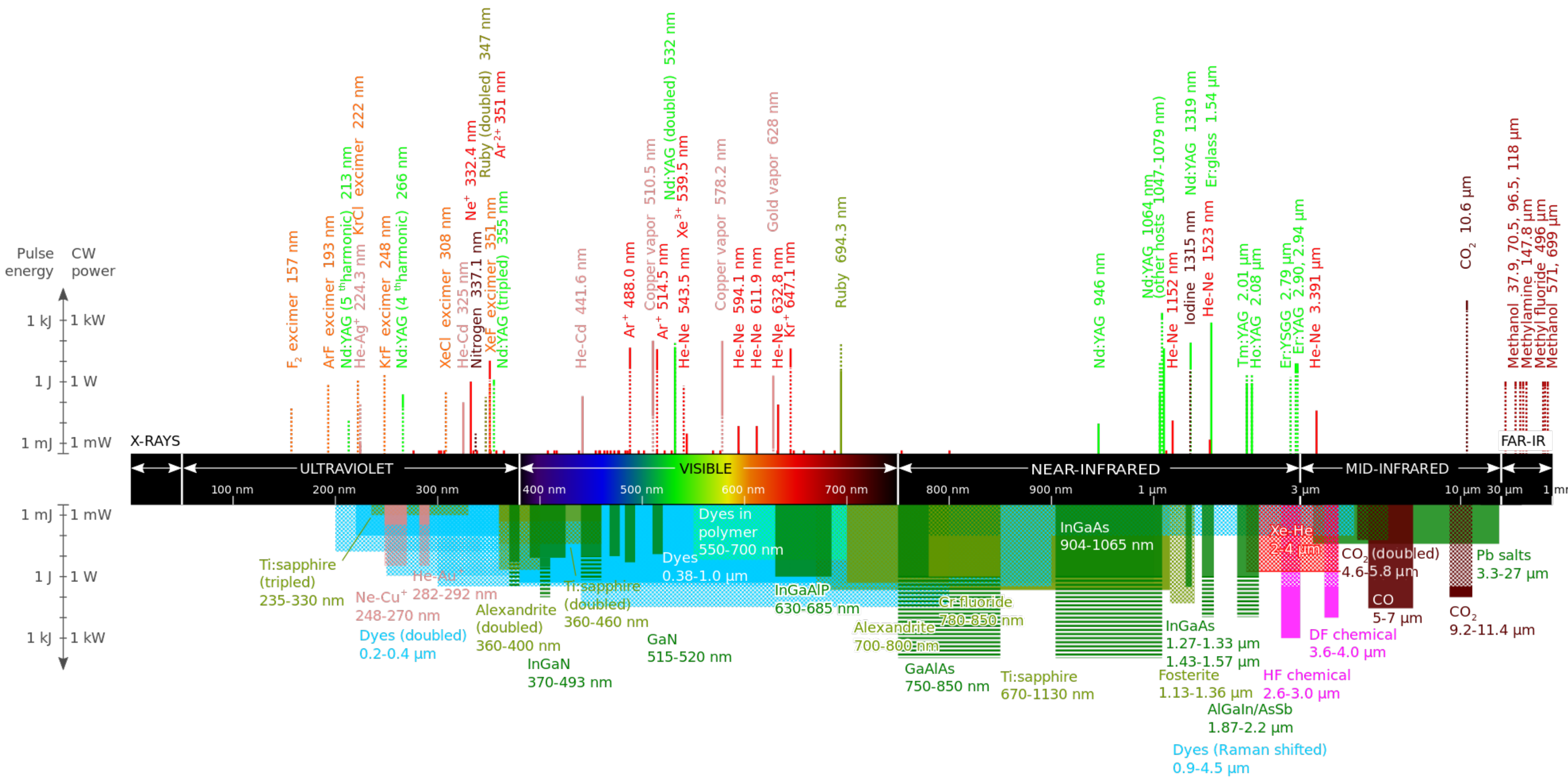
Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Holmium YAG (Ho:YAG) laser	2.1 µm	Laser diode	Tissue ablation, kidney stone removal, dentistry.
Chromium ZnSe (Cr:ZnSe) laser	2.2 - 2.8 µm	Other laser (Tm fiber)	MWIR laser radar, countermeasure against heat-seeking missiles etc.
Cerium doped lithiumstrontium (or calcium) aluminum fluoride(Ce:LiSAF, Ce:LiCAF)	~280 to 316 nm	Frequency quadrupled Nd:YAG laser pumped, excimer laser pumped, copper vapor laserpumped.	Remote atmospheric sensing, LIDAR, optics research.
Promethium 147 doped phosphate glass($^{147}Pm^{+3}$:Glass) solid-state laser	933 nm, 1098 nm	??	Laser material is radioactive. Once demonstrated in use at LLNL in 1987, room temperature 4 level lasing in ^{147}Pm doped into a lead-indium-phosphate glass étalon.
Chromium doped chrysoberyl (alexandrite) laser	Typically tuned in the range of 700 to 820 nm	Flashlamp, laser diode, mercuryarc (for CW mode operation)	Dermatological uses, LIDAR, laser machining.
Erbium doped and erbium–ytterbium codoped glass lasers	1.53-1.56 µm	Laser diode	These are made in rod, plate/chip, and optical fiber form. Erbium doped fibers are commonly used as optical amplifiers for telecommunications.
Trivalent uranium doped calcium fluoride (U:CaF_2) solid-state laser	2.5 µm	Flashlamp	First 4-level solid state laser (November 1960) developed by Peter Sorokin and Mirek Stevenson at IBM research labs, second laser invented overall (after Maiman's ruby laser), liquid helium cooled, unused today. [1]
Divalent samarium doped calcium fluoride (Sm:CaF_2) laser	708.5 nm	Flashlamp	Also invented by Peter Sorokin and Mirek Stevenson at IBM research labs, early 1961. Liquid helium cooled, unused today. [2]
F-Center laser.	2.3-3.3 µm	Ion laser	Spectroscopy

Some Semiconductor Lasers

Laser gain medium and type	Operation wavelength(s)	Pump source	Applications and notes
Semiconductor laser diode(general information)	0.4-20 µm, depending on active region material.	Electrical current	Telecommunications, holography, printing, weapons, machining, welding, pump sources for other lasers, high beam headlights for automobiles.[7]
GaN	0.4 µm		Optical discs. 405 nm is used in Blu-ray Discs reading/recording.
InGaN	0.4 - 0.5 µm		Home projector, primary light source for some recent small projectors
AlGaInP, AlGaAs	0.63-0.9 µm		Optical discs, laser pointers, data communications. 780 nm Compact Disc, 650 nm general DVD player and 635 nm DVD for Authoringrecorder laser are the most common lasers type in the world. Solid-state laser pumping, machining, medical.
InGaAsP	1.0-2.1 µm		Telecommunications, solid-state laser pumping, machining, medical..
lead salt	3-20 µm		
Vertical cavity surface emitting laser (VCSEL)	850–1500 nm, depending on material		Telecommunications
Quantum cascade laser	Mid-infrared to far-infrared.		Research, Future applications may include collision-avoidance radar, industrial-process control and medical diagnostics such as breath analyzers.
Hybrid silicon laser	Mid-infrared		Low cost silicon integrated optical communications

https://en.wikipedia.org/wiki/List_of_laser_types

Commercially Available Lasers



Wavelengths of commercially available lasers. Laser types with distinct laser lines are shown above the wavelength bar, while below are shown lasers that can emit in a wavelength range. The height of the lines and bars gives an indication of the maximal power/pulse energy commercially available, while the color codifies the type of laser material (see the figure description for details). Most of the data comes from Weber's book *Handbook of laser wavelengths*, with newer data in particular for the semiconductor lasers

https://en.wikipedia.org/wiki/List_of_laser_types

Masers/Lasers Discovery

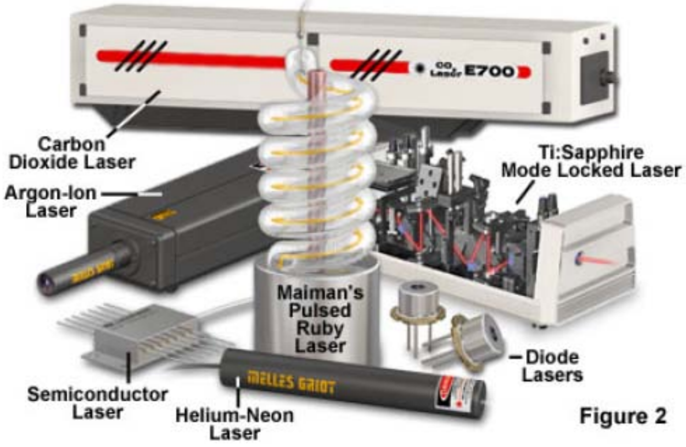
The Nobel Prize in Physics 1964

FOR FUNDAMENTAL WORK IN THE FIELD OF QUANTUM ELECTRONICS, WHICH HAS LED TO THE CONSTRUCTION OF OSCILLATORS AND AMPLIFIERS BASED ON THE MASER-LASER PRINCIPLE

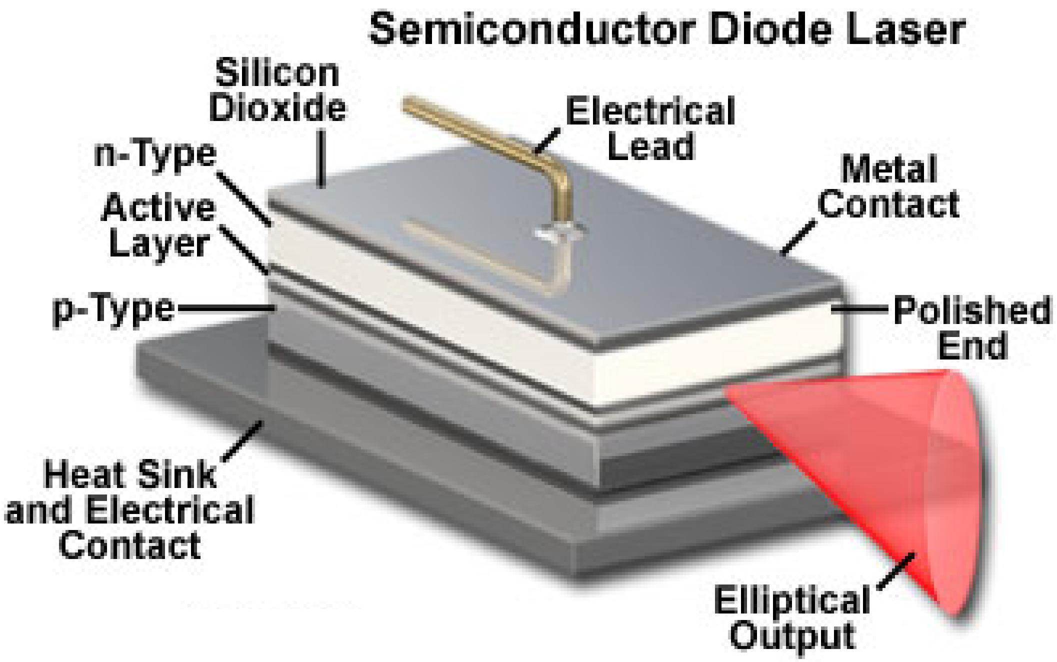
Charles H. Townes

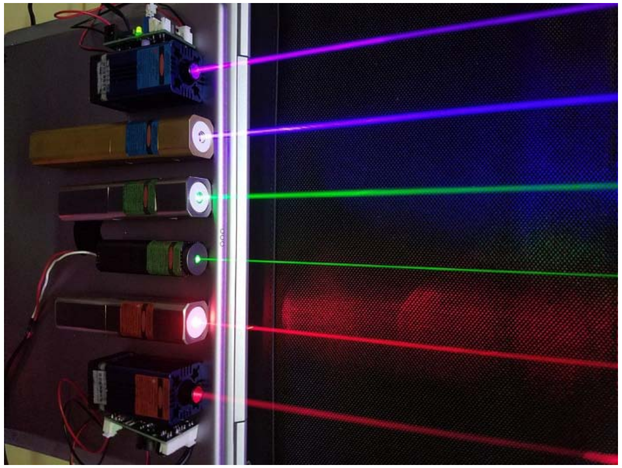
Nicolay G. Basov

Aleksandr M. Prokhorov

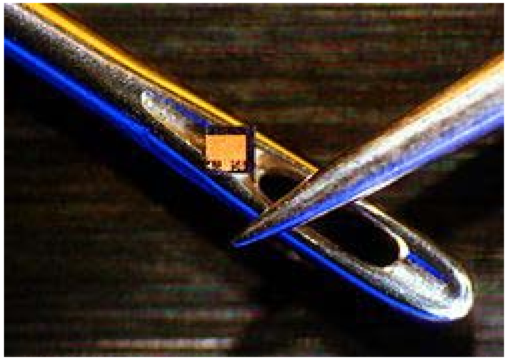


Semiconductor Laser Diode (LD)

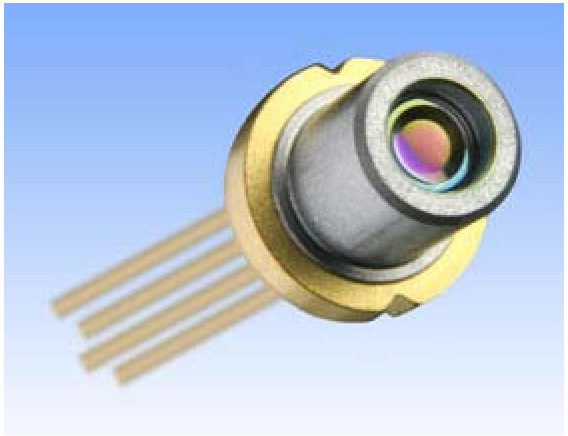




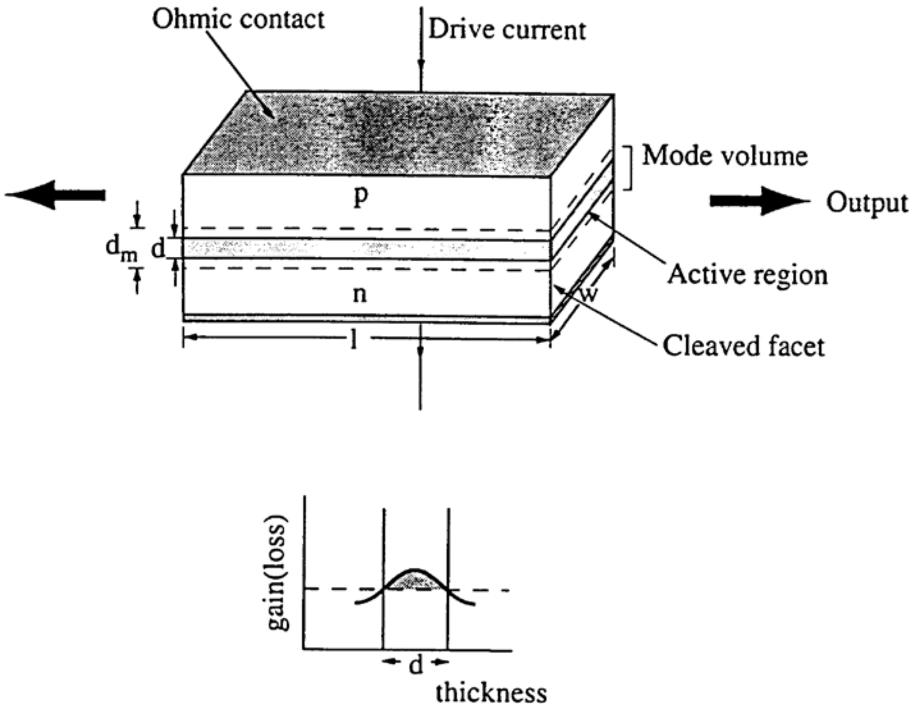
https://en.wikipedia.org/wiki/Laser_diode



Semiconductor Cleaved-Facet Laser



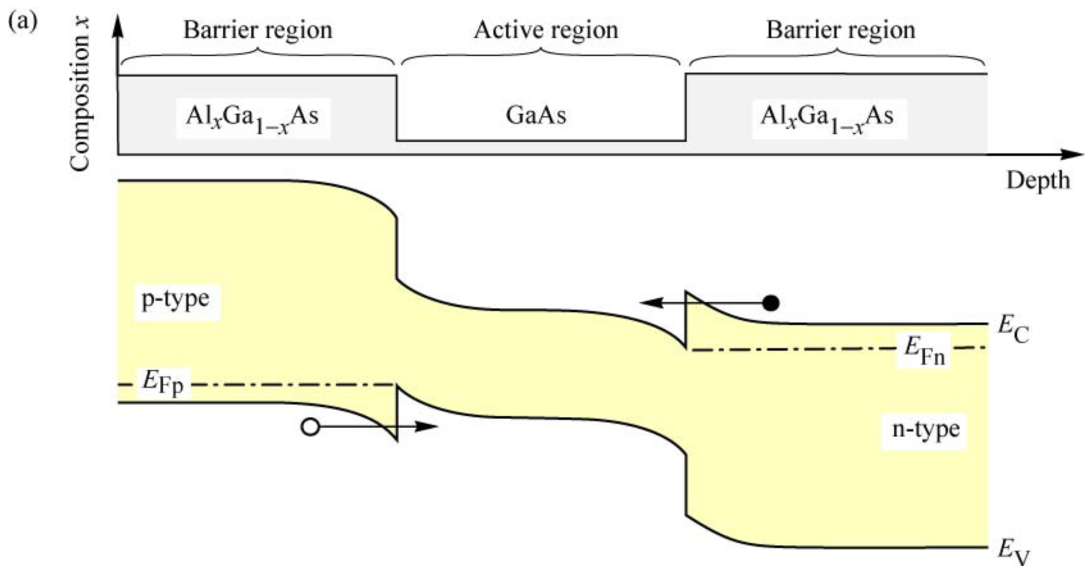
Oki Electric Industry Co., Ltd. 1490nm wavelength semiconductor laser (OL4636L-ET) that can transmit up to 2.5Gbps at an output level of 15mW, the industry's highest level over a temperature range of -40 to 85°C. This semiconductor laser is suitable for use in outdoor FTTH (Fiber-to-the-home) equipment.



Schematic of a broad-area junction laser with cleaved facets.

P. Bhattacharya, *Semiconductor Optoelectronic Devices.* New Jersey: Prentice Hall, 1997.

Semiconductor Laser Diode (LD)



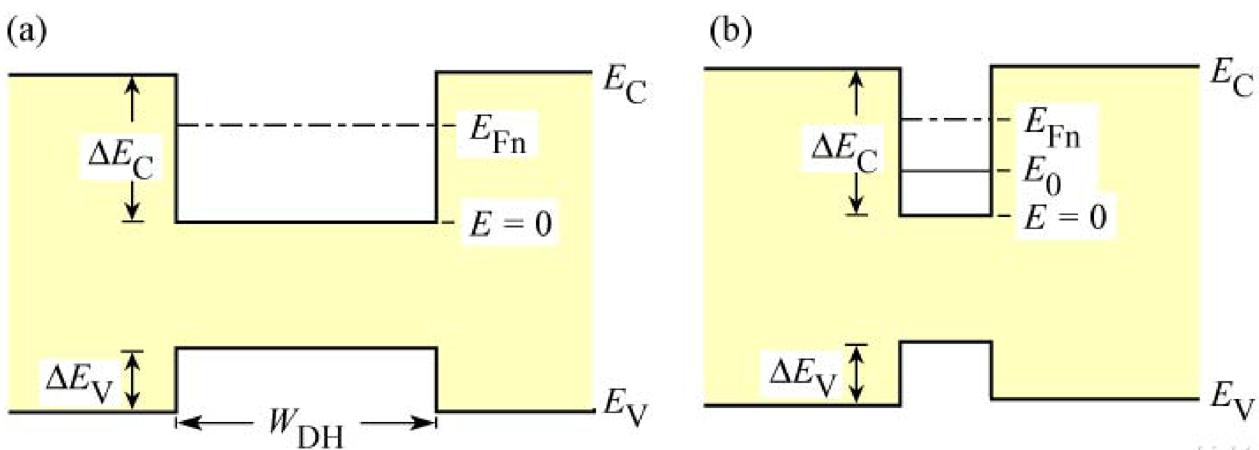
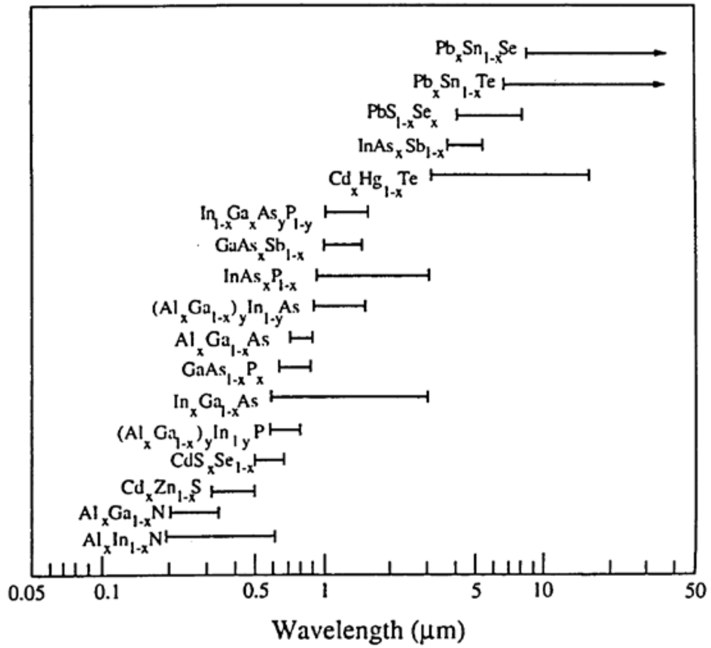


Fig. 4.10. Fermi level (E_{Fn}) and subband level (E_0) in (a) a double heterostructure and (b) a quantum well structure.

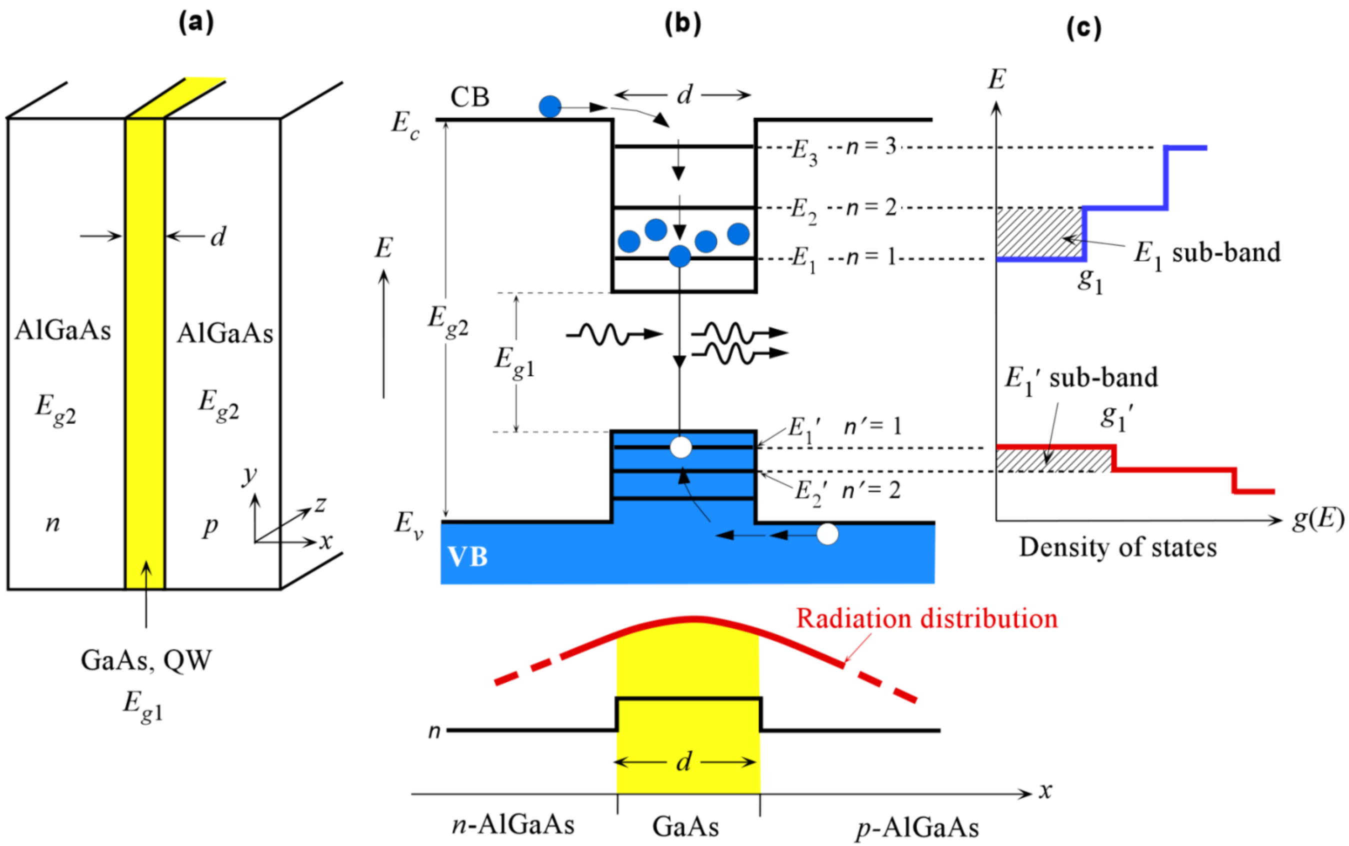
E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Semiconductor Lasers



Compound and alloy semiconductor lasers. The narrow bandgap devices require cooling for operation.
B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics.* New York: Wiley, 1991.

Semiconductor Quantum-Well Lasers

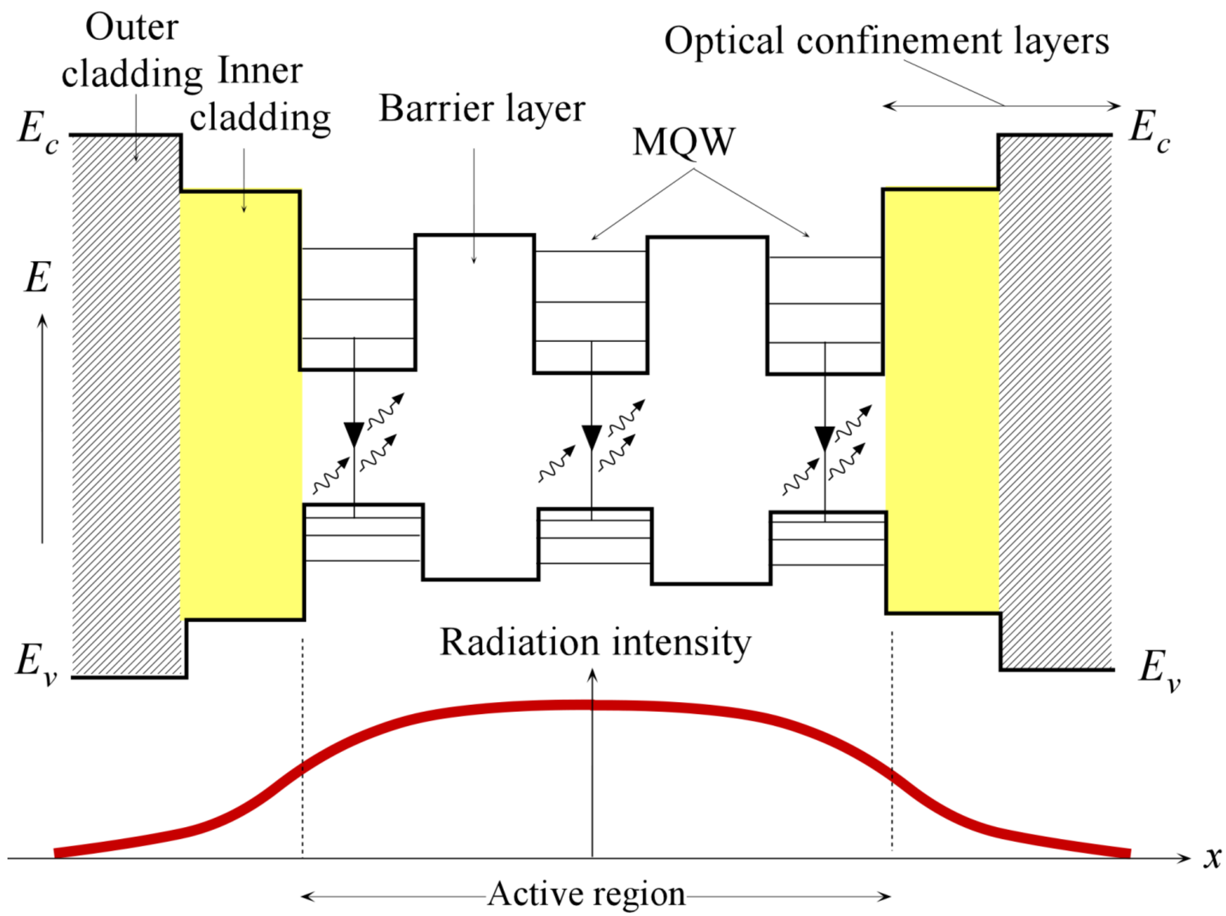


(a) A single quantum well (SQW) of bandgap E_{g1} sandwiched between two semiconductors of wider bandgap E_{g2}, **(b)** The electron energy levels, and stimulated emission. The electrons and holes are injected from *n*-AlGaAs and *p*-AlGaAs respectively. The refractive index variation tries to confine the radiation to GaAs but *d* is too thin, and most of the radiation is in the AlGaAs layers rather than within *d*. **(c)** The density of sates $g(E)$ is a step-like function, and is finite at E_1 and E_1'. The E_1 sub-band for electrons and E_1' sub-band for holes are also shown. The electrons in the E_1 sub-band have kinetic energies in the *yz*-plane.

From "Slideshare " Presentation 8155037.ppt

https://www.google.gr/url?sa=i&source=images&cd=&ved=2ahUKEwif3J6Vo8fgAhXKblAKHWQ3AUQQjxx6BAgBEAI&url=https%3A%2F%2Fslideplayer.com%2Fslide%2F8155037%2F&psig=AOvVaw0llH5hwweS9b0go5RpkJ-i&ust=1550647735430885

Semiconductor Quantum-Well Lasers



A simplified schematic diagram of multiple quantum well (MQW) heterostructure laser diode. Electrons are injected by the forward current into quantum wells. The light intensity distribution is also shown. Most of the light is in the active region.

From "Slideshare " Presentation 8155037.ppt

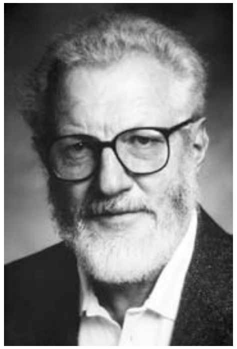
https://www.google.gr/url?sa=i&source=images&cd=&ved=2ahUKEwif3J6Vo8fgAhXKblAKHWQ3AUQQjxx6BAgBEAI&url=https%3A%2F%2Fslideplayer.com%2Fslide%2F8155037%2F&psig=AOvVaw0llH5hwweS9b0go5RpkJ-i&ust=1550647735430885

Semiconductor Lasers

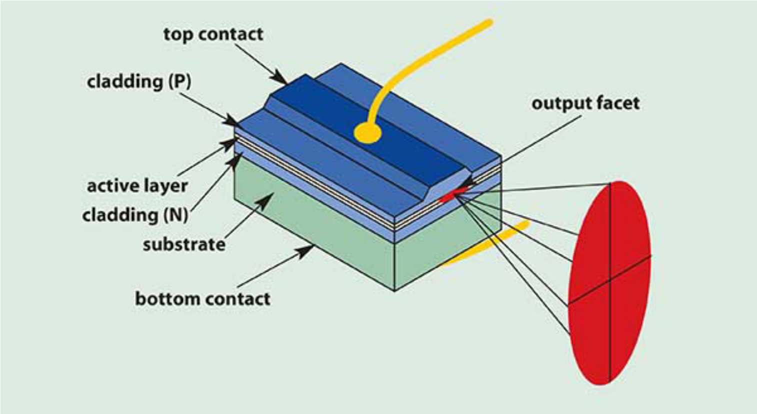
The Nobel Prize in Physics 2000

FOR DEVELOPING SEMICONDUCTOR HETEROSTRUCTURES USED IN HIGH-SPEED- AND OPTO-ELECTRONICS

Zhores I. Alferov



Herbert Kroemer



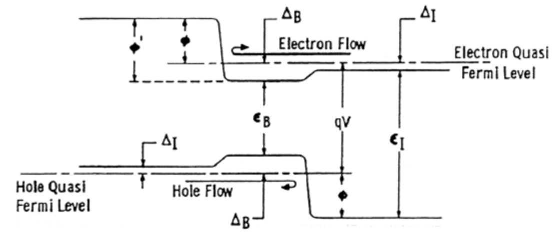


Figure 6: *An energy diagram of a semiconducting heterojunction showing that electrons pass the barrier while holes are reflected, or vice versa depending upon the doping and ratios of band gaps on either side of the junction. Combining two junctions, it is possible to confine charge carriers to the region of the lower bandgap as well as photons in a double heterostructure laser. The drawing is taken from a paper by H. Kroemer, Proc. IREE* ***51****, 1782 (1963).*

http://www.nobelprize.org/nobel_prizes/physics/laureates/2000/press.html