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TOM
Tailored Optical Materials

Anorganische Konvertermaterialien zur Erzeugung von 200-240 nm Strahlung

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27. DAfP-Tagung:
Licht in der Medizin, Biologie und Technik

Quedlinburg, 07. Juli 2023

UV Radiation

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History across the last 222 years….

1801 — **Discovery by Johann W. Ritter due to effect of dispersed solar light on $AgNO_3$ → Ag (black) → Chemistry as the basis of the photographic process**

1902 — **UV radiation kills microorganisms**

1970 — **Photolithography by Hg discharge lamps**

Early 70's — **g-line (434 nm)**

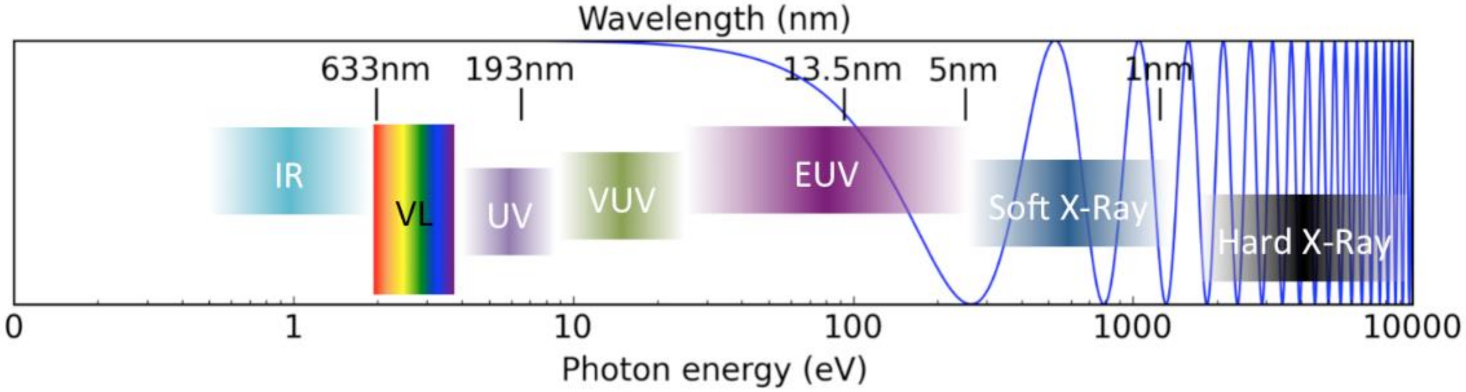
Early 80's — **i-line (365 nm)**

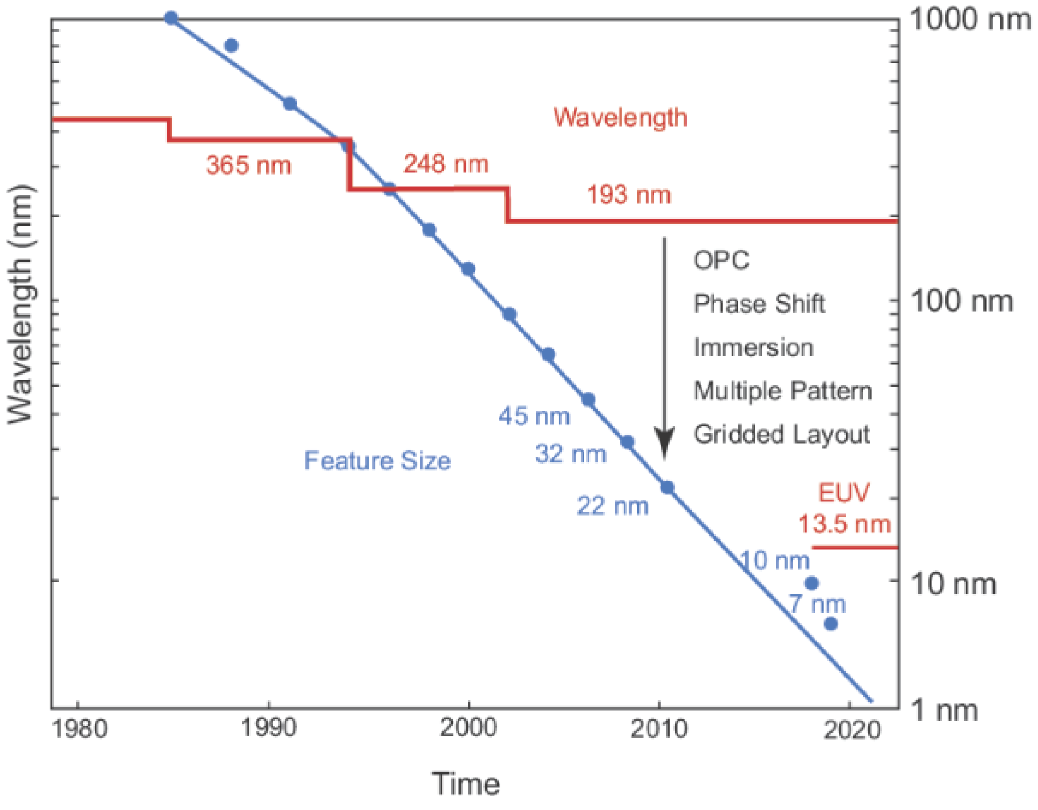
1990 — **KrF* laser (248 nm) → Deep UV photolithogr.**

2000 — **ArF* laser (193 nm)**

2017 — **Sn* plasma (13.5 nm) → EUV lithography**

ASML, NL (€6 billion in R&D over 17 years)





Outline

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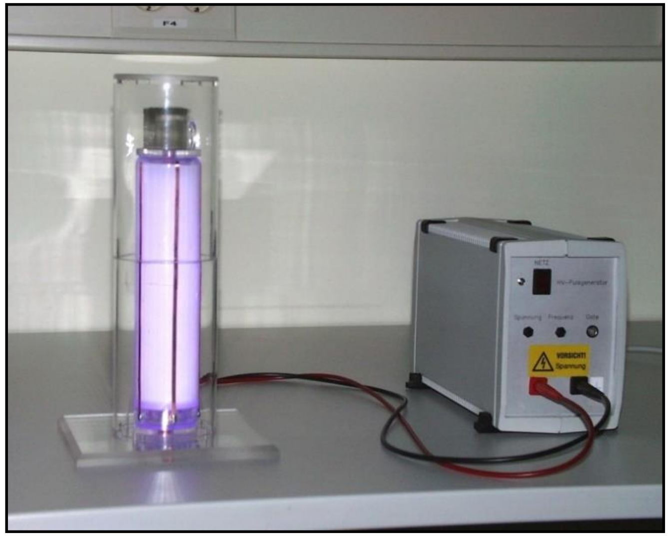

Source: http://www.instanttrust.com/en/double-blue/

1. Motivation

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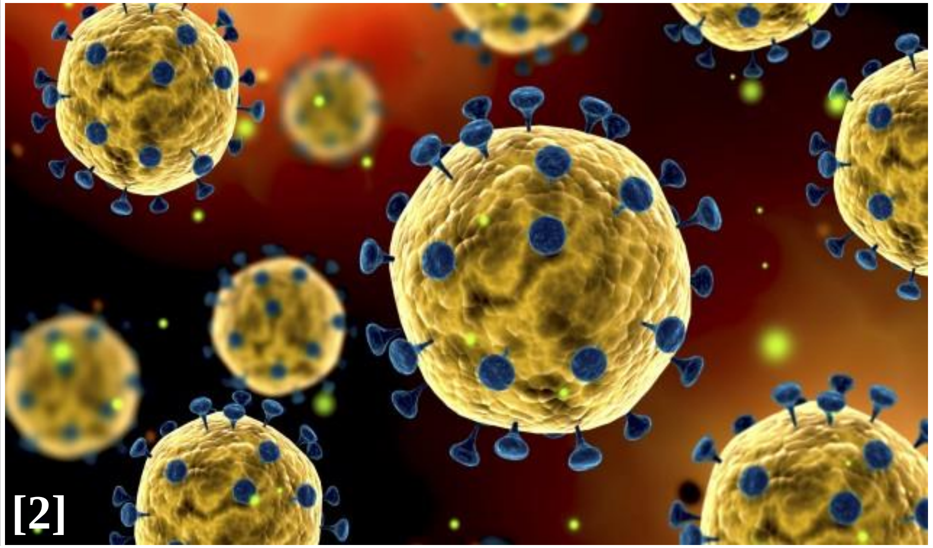
Outbreaks, Epidemics and Pandemics of some Airborne Viral Diseases

Period	Virus/ -type	Spread	Remarks
1917 - 1920	Spanish flu	Worldwide	Death toll > $1 \cdot 10^8$
2002 - 2003	SARS-CoV-1	Worldwide	
since 2004	Marburg	Angola and Uganda	Aerosols play a minor role, but are not insignificant
2004 - 2016	A/H5N1	Worldwide	Aerosols hardly play a role, but transmission by aerosol droplets is possible
2009 - 2010	H1N1	Worldwide	
2019 - today	SARS-CoV-2	Worldwide	Death toll by 07/23 ~ $6.9 \cdot 10^6$ [3]
Yearly	Influenza	Worldwide	Estimated 290,000 to 645,000 people die each year [1]

Viruses = Volatile nanoparticles often spread by aerosols



Literature

[1] A. Danielle Iuliano et al., Estimates of global seasonal influenza-associated respiratory mortality: A modelling study, The Lancet, Volume 391, Issue 10127, P1285-1300, March 31, 2018 https://doi.org/10.1016/S0140-6736(17)33293-2

[2] Corona-Update: Wie weit ist die Forschung? DAZ.online, 12.03.2020

[3] Worldometer: https://www.worldometers.info/coronavirus/

1. Motivation

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Disinfection of Air, Water, and Surfaces

<u>Thermal treatment</u>

Drinking water: T > 70 °C

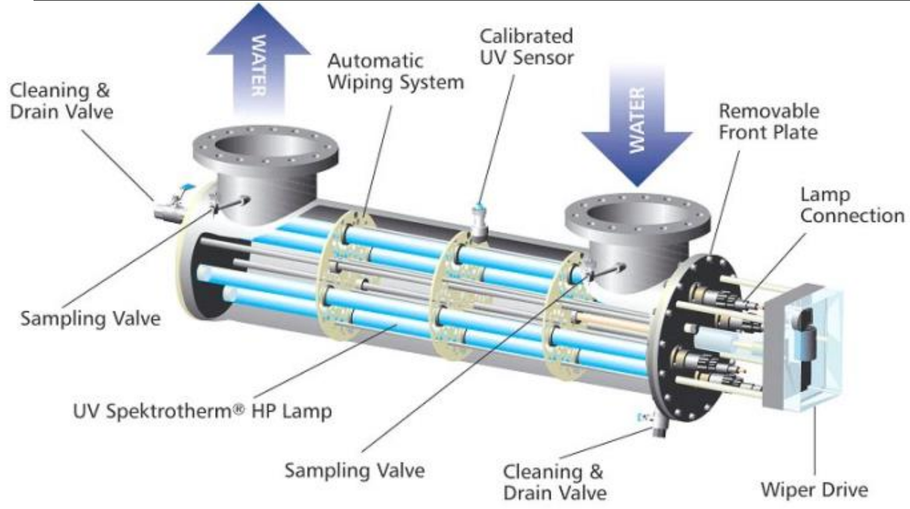
Surfaces: T > 120 °C

Drawback: Energy demand due to high heat capacity of water (and humid air)

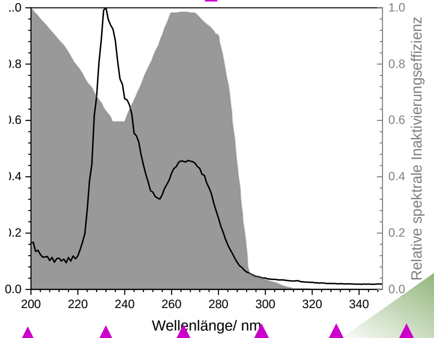
Heating of 1 m³ H_2O from 10 to 70 °C

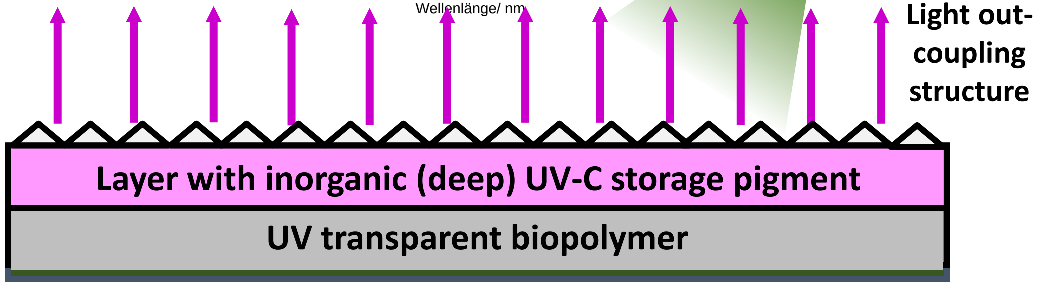
$$\Delta Q = m * c * \Delta T$$
$$= 1000 \text{ kg} * 4.19 \text{ kJ/kgK} * 60 \text{ K}$$
$$\sim 250000 \text{ kJ}$$
$$\sim 700 \text{ kWh/m}^3$$

<u>UV-C treatment of air, water, occupied spaces, or surfaces in use</u>



UV-C Spectrum





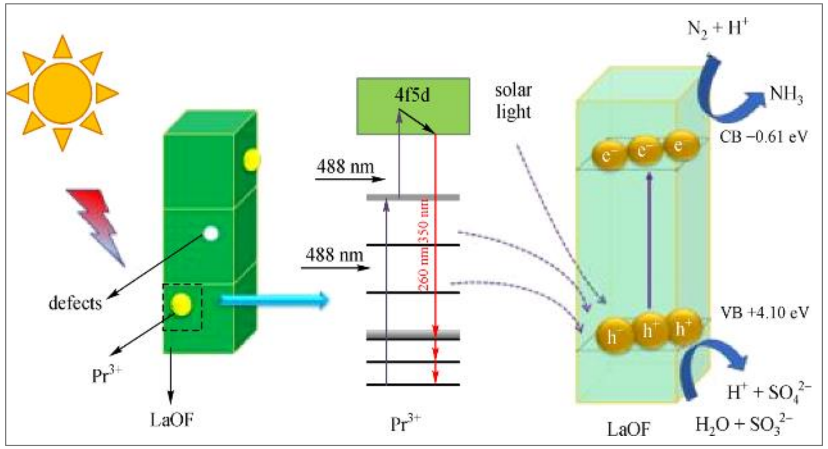
Al layer as UV/Vis reflector

Typical 0.2 – 10 kWh/m³ (Ref.: Dr. M. Salvermoser, Xylem)

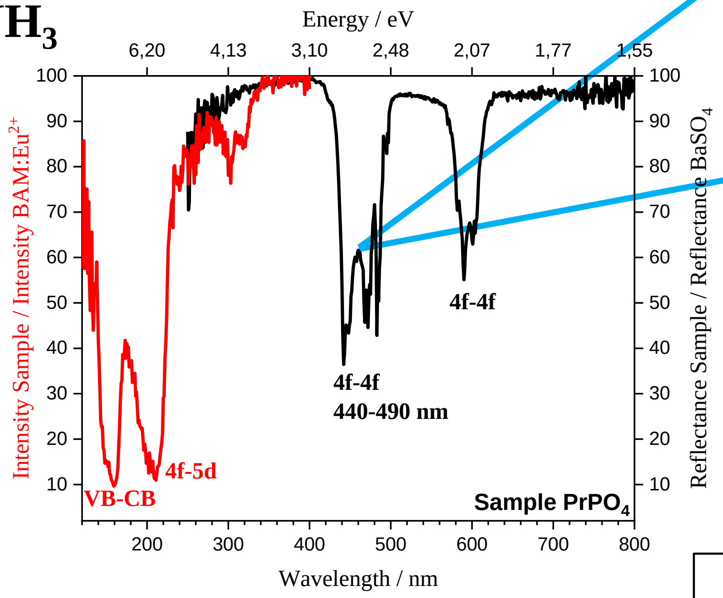
1. Motivation

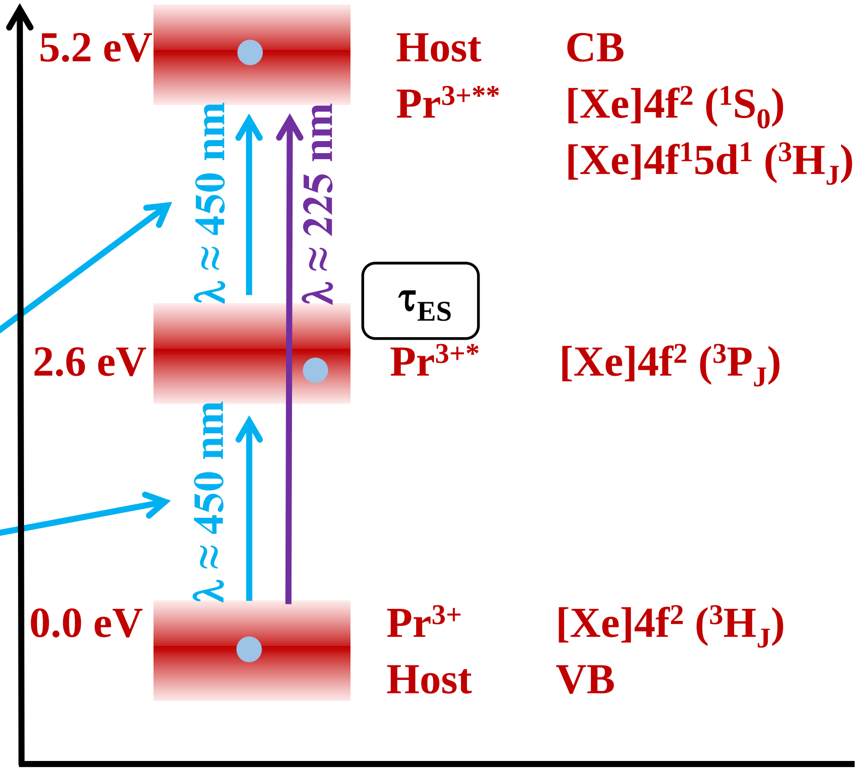
Photochemistry: New Way to Produce Ammonia?

- **Haber-Bosch (α-Fe)** $N_2 + 3\ H_2 \leftrightarrows 2\ NH_3$ (400 - 500 °C)
- **Nitrogenases (Fe^{n+})** $2\ N_2 + 10\ H^+ + 8\ e^- \leftrightarrows 2\ NH_4^+ + H_2$ (RT)
- **Heterogenous photocatalysis by up-conversion induced photoionisation:**
  Semiconductor (SC) + blue laser ⟶ SC* ⟶ SC** ($e^-_{CB} + h^+_{VB}$)
  $e^-(CB) + N_2 \longrightarrow (N_2)^-$
  $6\ (N_2)^- + 6\ H_2O \longrightarrow 6\ OH^- + 5\ N_2 + 2\ NH_3$



Phocatalytical NH_3 synthesis at LaOF:Pr





Simplified energy level scheme of Pr^{3+}

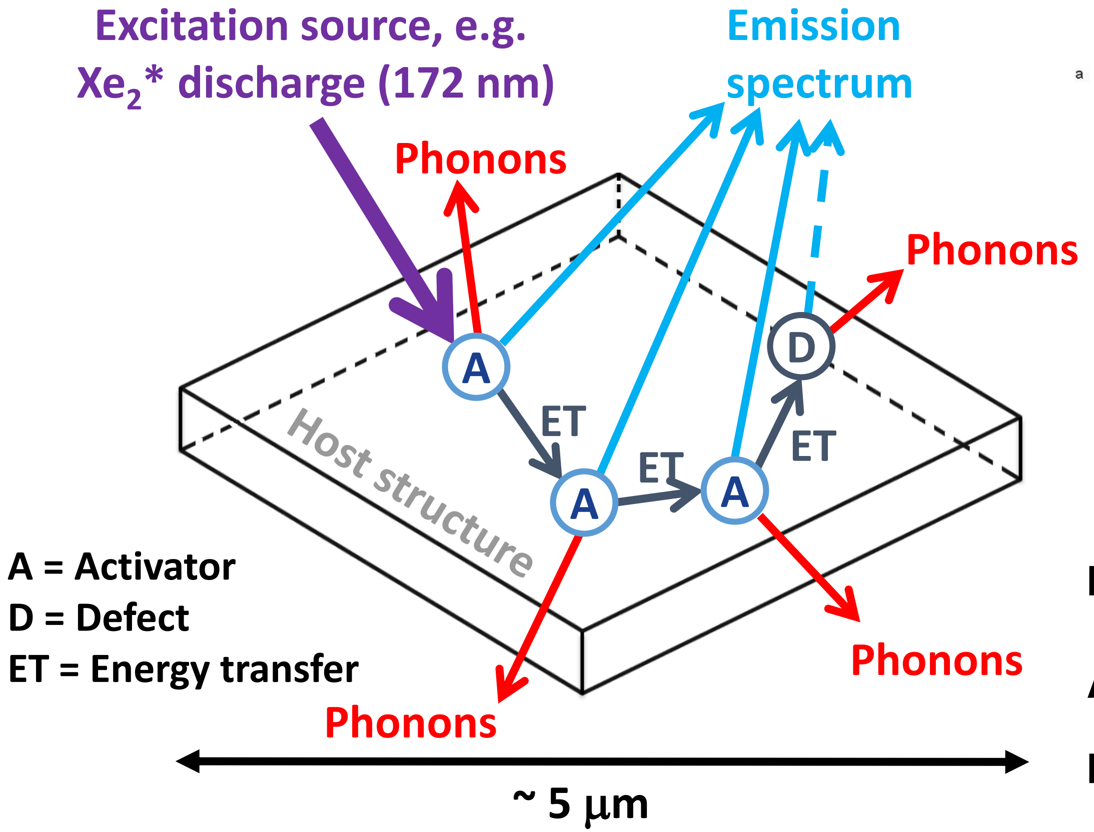
Need: 225 nm radiation source for photocatalytic N_2 activation

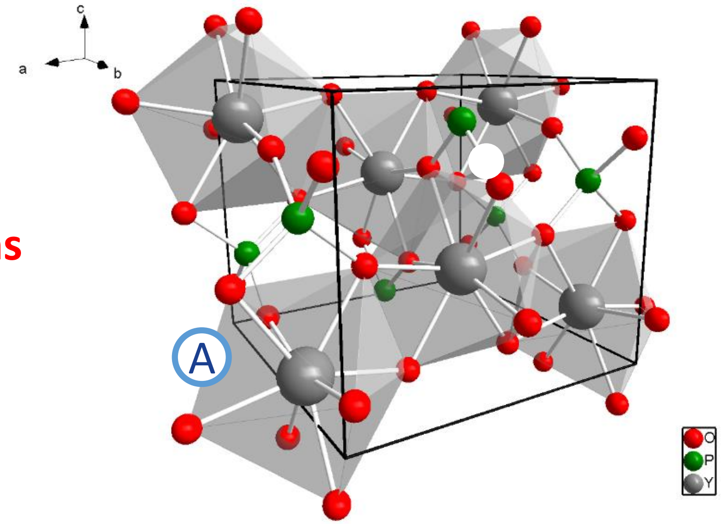
Lit.: LaOF-Pr MW hydrothermal synthesis for photocatalytic N fixation, Front Mater Sci. 14 (2020) 43

2. Inorganic Conversion Materials

Working Principle

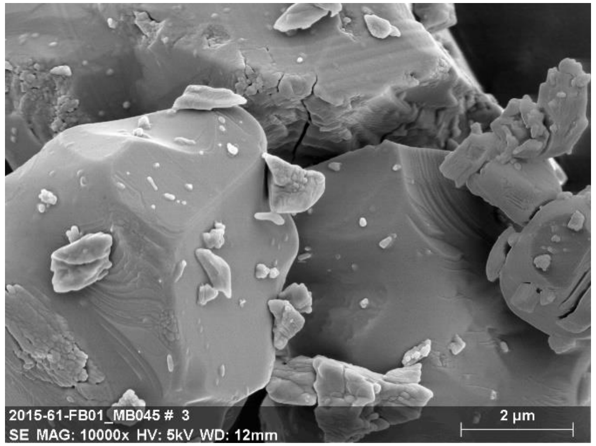
1. Excitation — Absorption of energy from external source (hν, e^-, x-rays, E-field)
2. Energy transfer (ET) — To activator ions or defects (storage and afterglow)
3. Relaxation — Radiative: Emission (luminescence) → Luminescent pigments
   Non-radiative: Heat (phonons) → Absorption pigments (filter)





Host structure, e.g. YPO_4 or $LuPO_4$

SEM image of $YPO_4:Bi^{3+}$



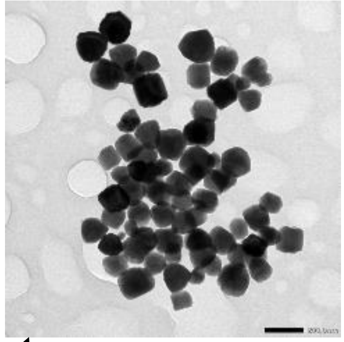
Typical particle size 1 - 10 µm

Activator ion (A): Sc^{3+}, Ce^{3+}, Pr^{3+}, Nd^{3+}, Gd^{3+}, Bi^{3+}

Lit.: W.O. Milligan, Inorg. Chim. Acta 60 (1982) 39

2. Inorganic Conversion Materials

Excitation Sources for Deep UV Emission by Micro- or Nanoscale Conversion Materials



X-Ray Tube Neptune 5200
Voltage Range: 10 - 50 kV
Max. Power: 100 W

Scintillation

Americium source,
α- and γ-Radiation

Up-Conversion

Fianium Supercontinuum SC450-4 White Light Laser, wavelength range 460 nm to 2.4 µm

Various high power LEDs from 250 to 1100 nm

Down-Conversion

Deuterium bulb, wavelength range 120 to 400 nm

Xenon lamp, wavelength range 200 nm to 900 nm

EPL ps Laser, wavelength 265, 375, and 445 nm

Continuous laser, wavelength 375, 405, 445, and 488 nm

2. Inorganic Conversion Materials

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Relevant Properties of Deep UV Emission by Micro- or Nanoscale Conversion Materials

Exc. and emission spectra

Quantum yield (QY)

Germicidal efficacy (%)

Spectral consistency

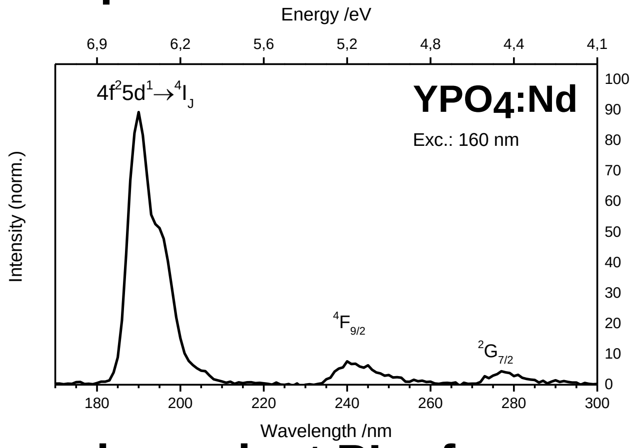
Decay curve

Thermal quenching

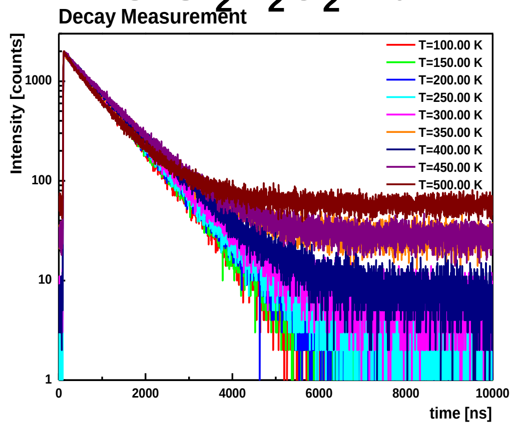
Linearity

Stability in manufacturing process and in operation

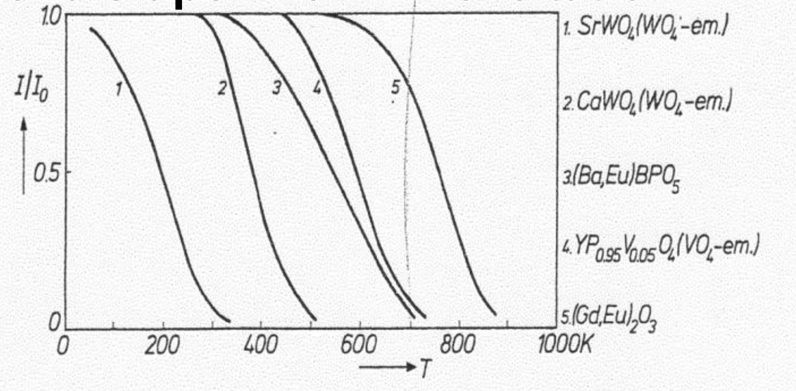
Emission spectrum of YPO_4:Nd upon 160 nm excitation



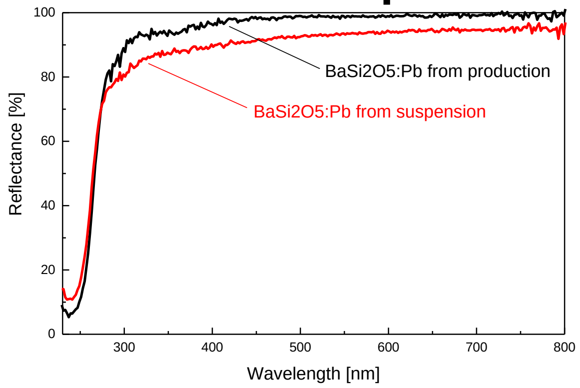
Decay curves of $SrSi_2N_2O_2$:Eu



Temp. dependent PL of conversion materials upon 254 nm excitation

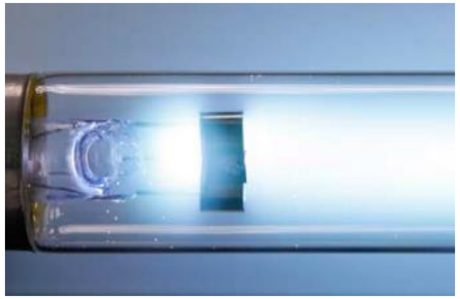


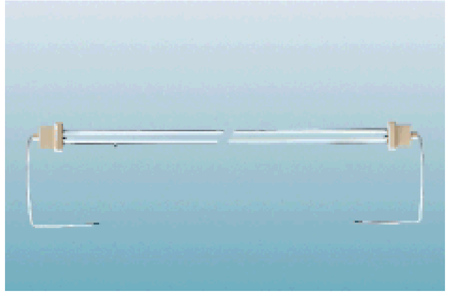
Reflection spectrum of $BaSi_2O_5$:Pb before and after processing



3. UV Radiation Sources

For the Deep UV-C Range

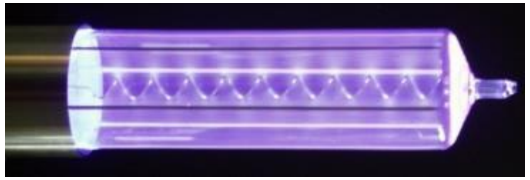




Hg discharge lamps
- low pressure — 185, 254 nm
- amalgam — 185, 254 nm
- medium pressure — 200 – 400 nm

D_2 discharge lamps — 110 – 400 nm

Excimer laser
- ArF* — 193 nm



Excimer discharge lamps, e.g. Dielectric Barrier Discharge (DBD) lamps
- KrBr* — 207 nm
- KrCl* — 222 nm
- Xe_2* + UV phosphor (fluorescent DBD) — 190 – 400 nm

(Al,Ga)N UV LEDs — 210 – 365 nm

X-ray tube + UV phosphor — 190 – 400 nm

Cathode ray tube + UV phosphor — 190 – 400 nm

Blue laser or blue LED + up-converter — 200 – 250 nm

3. UV Radiation Sources

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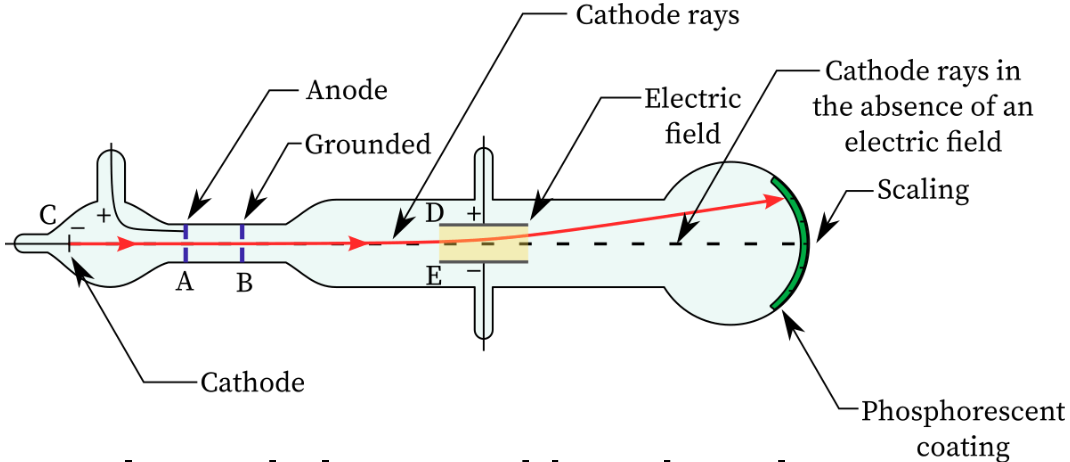
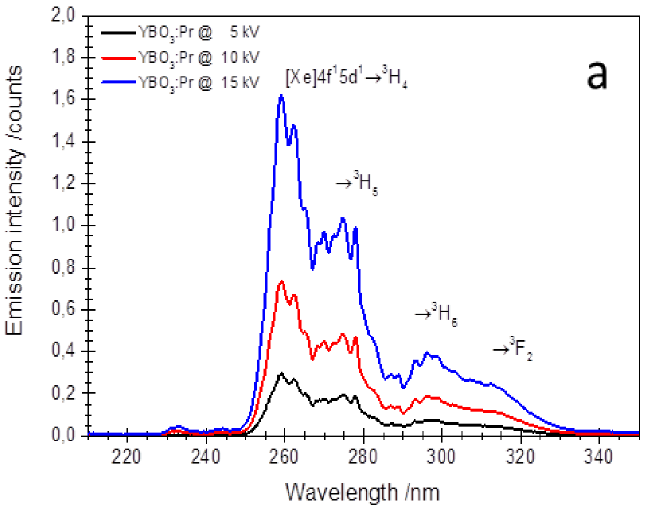
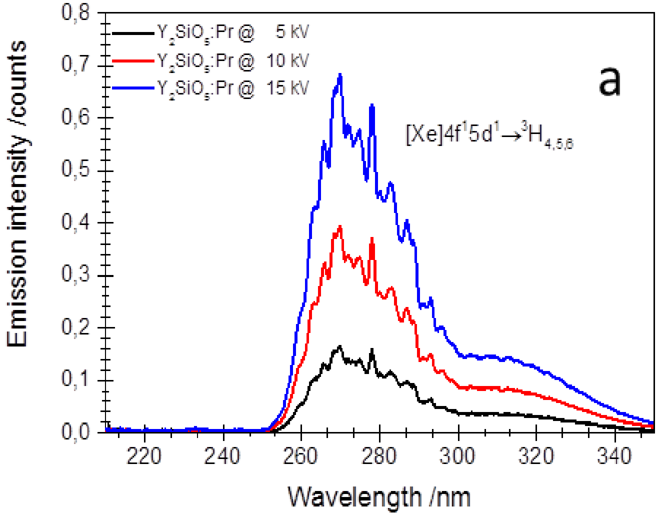
Cathode Ray Tube (CRT) with UV-C Converter YBO_3:Pr or Y_2SiO_5:Pr



YBO_3:Pr and Y_2SiO_5:Pr^{3+} spectra upon e^- excitation





Accelerated electrons hit a phosphor screen to yield cathodoluminescence (CL): The principle is similar to that of a cathode ray tube for TV sets/monitors

Lit.: J. Silver, M. Broxtermann, T. Jüstel et al., ECS J. SSST 6 (2017) R47

3. UV Radiation Sources

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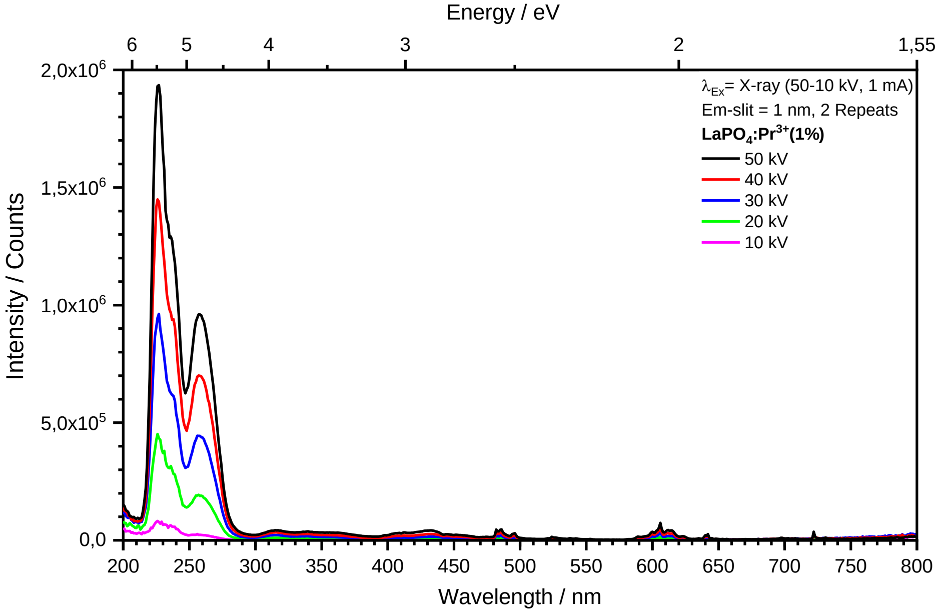
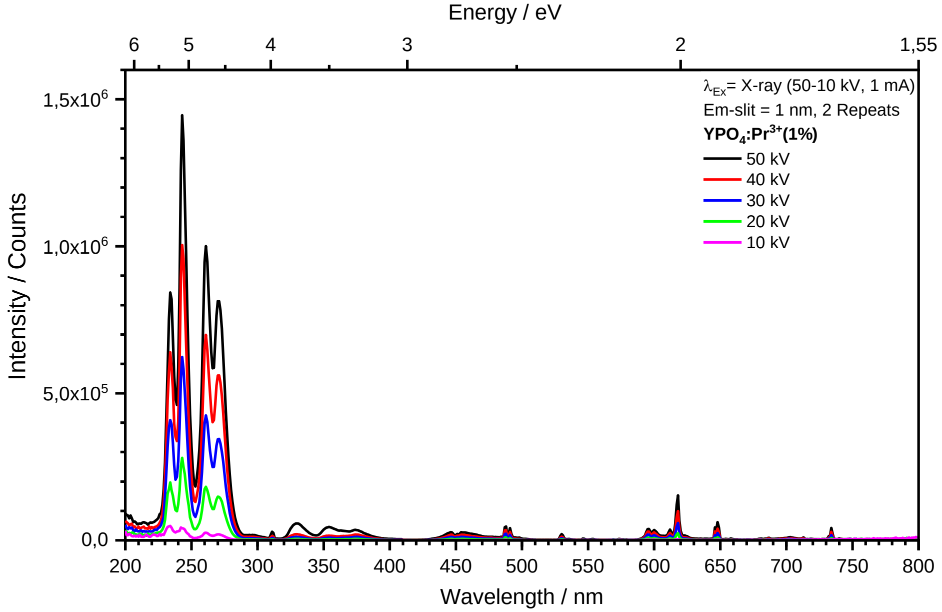
X-ray Tube with UV-C Converter $LaPO_4$:Pr or YPO_4:Pr

$LaPO_4$:Pr upon 10 – 50 keV excitation



YPO_4:Pr upon 10 – 50 keV excitation



Pr^{3+} doped ortho-phosphates ($LuPO_4$) and ortho-silicates (Lu_2SiO_5) are efficient UV-C emitting scintillators

Spin-off: Cancer treatment by $LnPO_4$:Pr,Nd (Ln = Y, La, Lu)

Lit.: J. Kappelhoff, J.N. Keil, M. Kirm, V. Makhov, K. Chernenko,. S. Möller, T. Jüstel, J. Chem. Phys. 562 (2022) 111646

3. UV Radiation Sources

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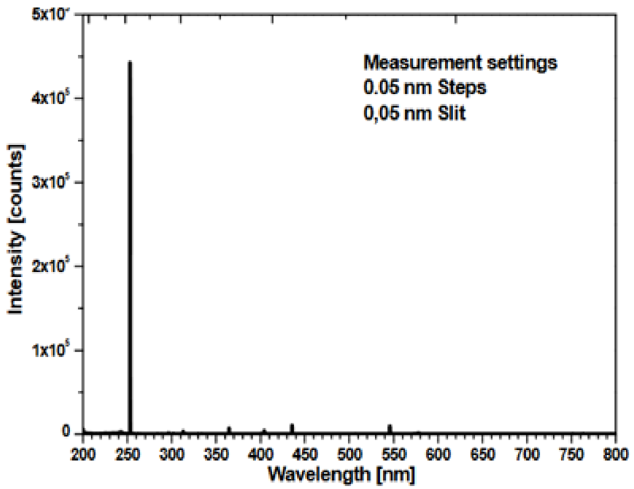
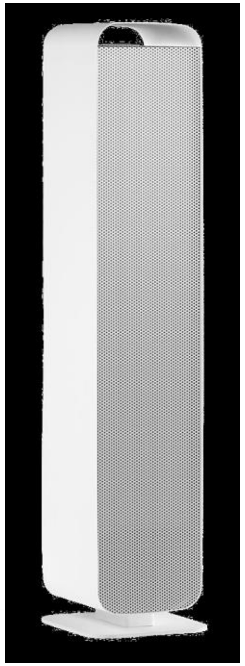
Main Application Areas: Water and Indoor Air or Surface Disinfection

Standard: Hg discharge lamps (LP, MP, HP)

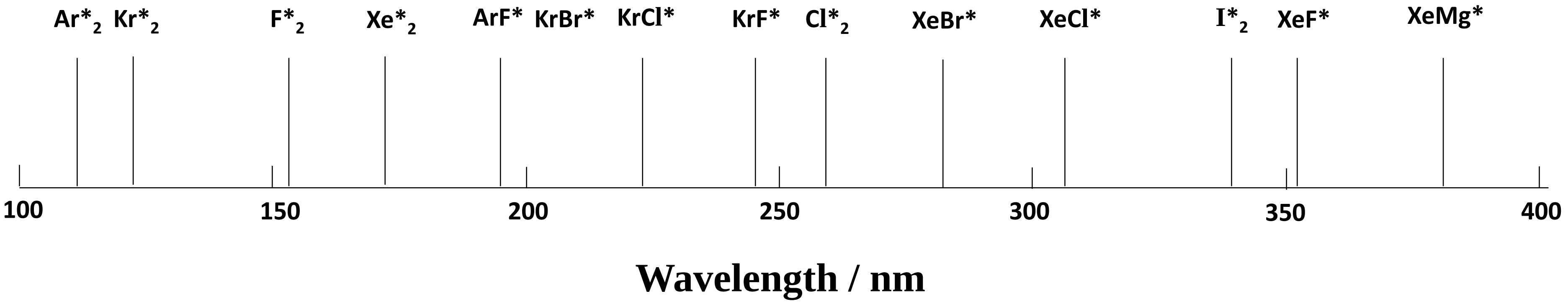
- 253.7 nm (Hg*) radiation is very effective
- Hazardous towards skin and eyes → closed device requi
- 185.0 nm Hg line is filtered off to prevent O_3 formation





Excimer discharge lamps

- Excimer lamps emit in the VUV or UV range with high power density
- Lamp filling, e.g. Xe or Kr and X_2, govern emission spectrum & efficiency



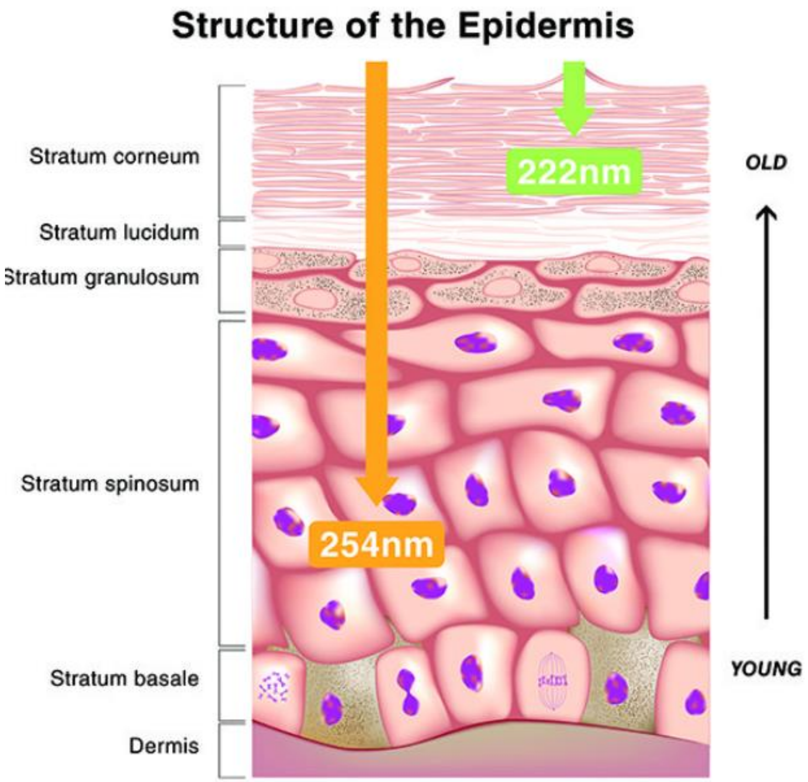
STAMBOLI Air Purifier

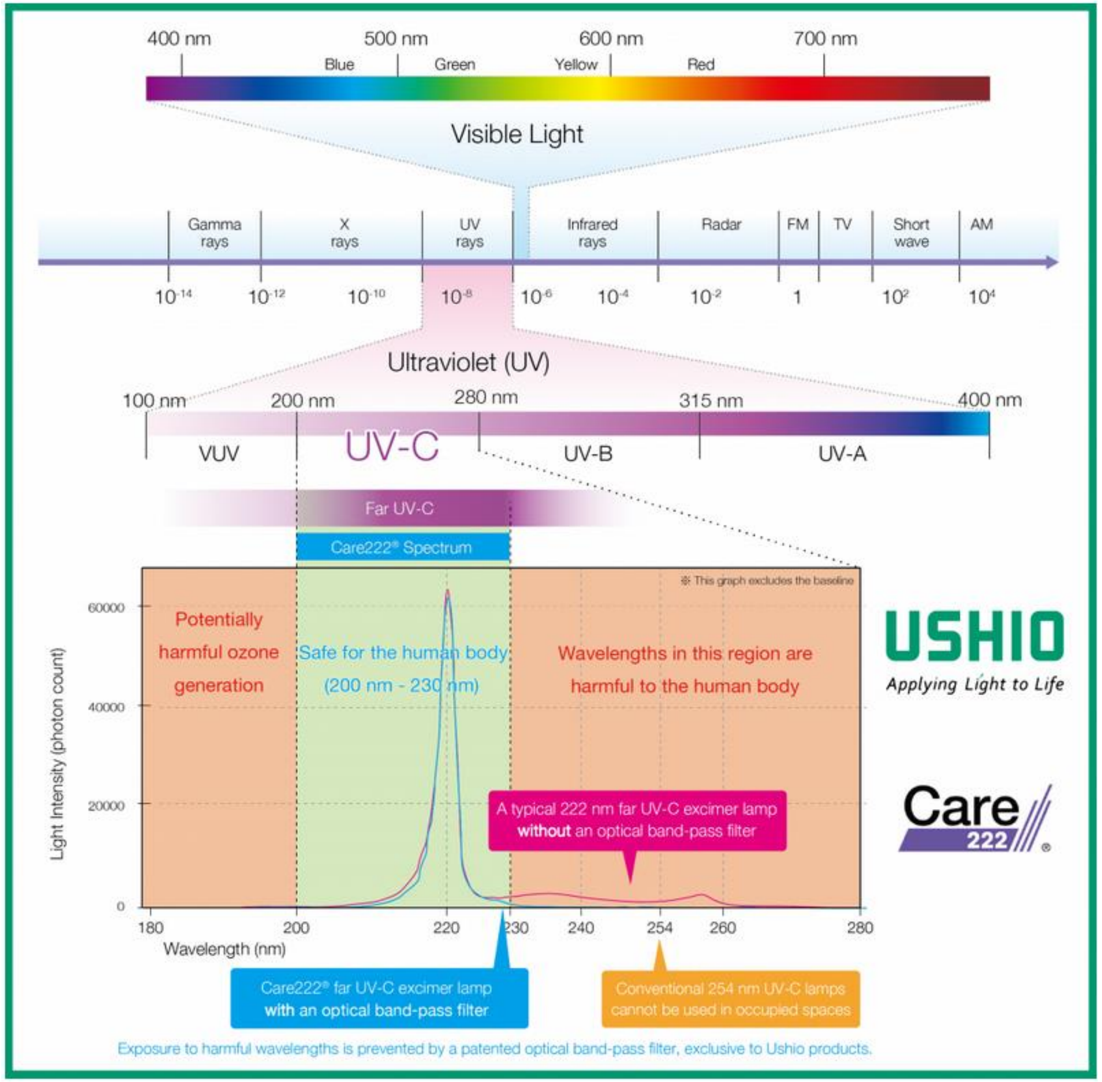
- Air flow: 160 m^3 h^{-1}
- Light sources: Hg LP UV-C lamp (253.7 nm), ozone free
  - Voltage: 220 - 240 V
- Input power: 72 W
- UVC output: ~ 30 W
- Lifetime of UV-C lamps ~ 9000 hours

4. Excimer Discharge Lamps

Care222® Ushio

Commercial product of Ushio
“for eye and skin safe indoor disinfection”





Source: Ushio Homepage

4. Excimer Discharge Lamps

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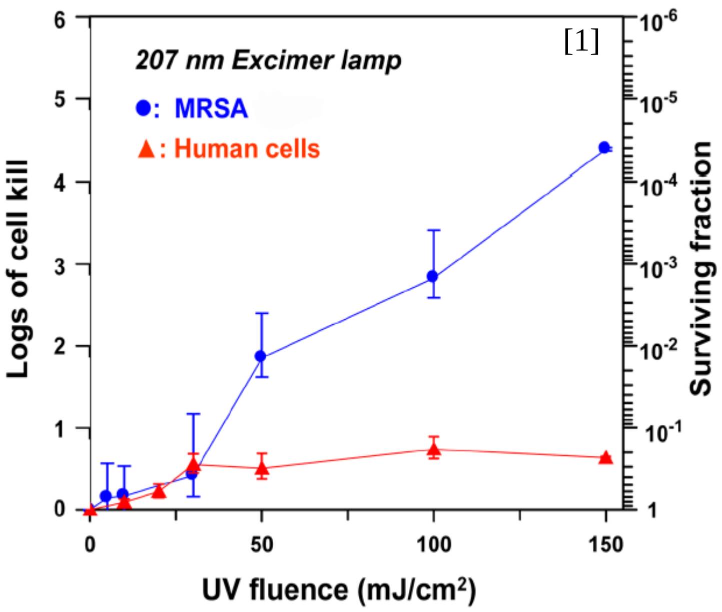
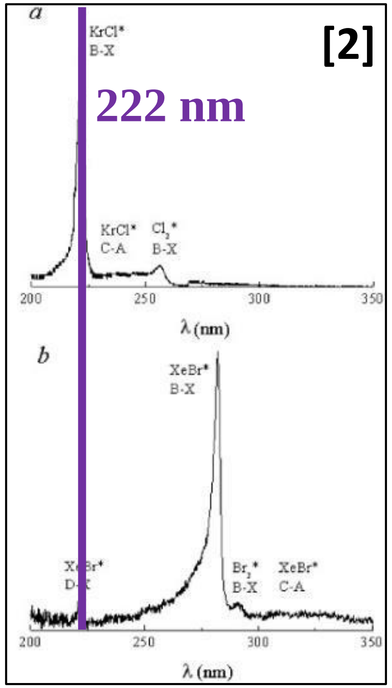
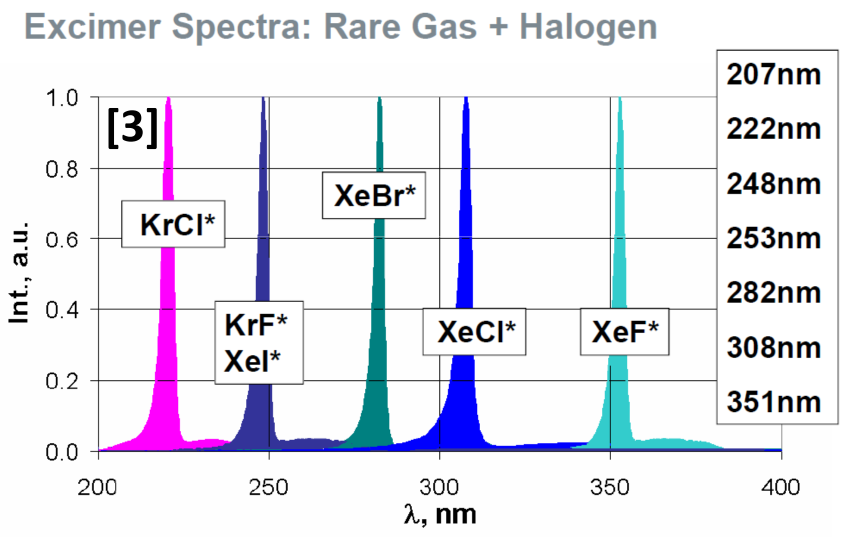
Novel Application – Indoor Air Disinfection with Deep UV-C

- **Recent publications on the influence of deep UV-C radiation on human skin and eye cells showed, that radiation between 207 and 222 nm efficiently kills pathogens potentially without harm to exposed human tissues [1]**
- **KrBr* excimer discharge lamps (207 nm) have been successfully tested**
- **Alternative: KrCl* excimer discharge (222 nm) shows undesired spectral features above 230 nm (Cl_2*)**







Lit.:[1] D.J. Brenner et al., Radiat. Res. 187 (2017) 483
[2] M. Erofeev, V.F. Tarasenko, Quantum Electronics, 2008, 38, 401-403
[3] A. Voronov, Heraeus, Übersicht der UV-Lampen und ihre Einsatzgebiete, Darmstadt Oktober 2009

5. Deep UV-C Emitting Converters

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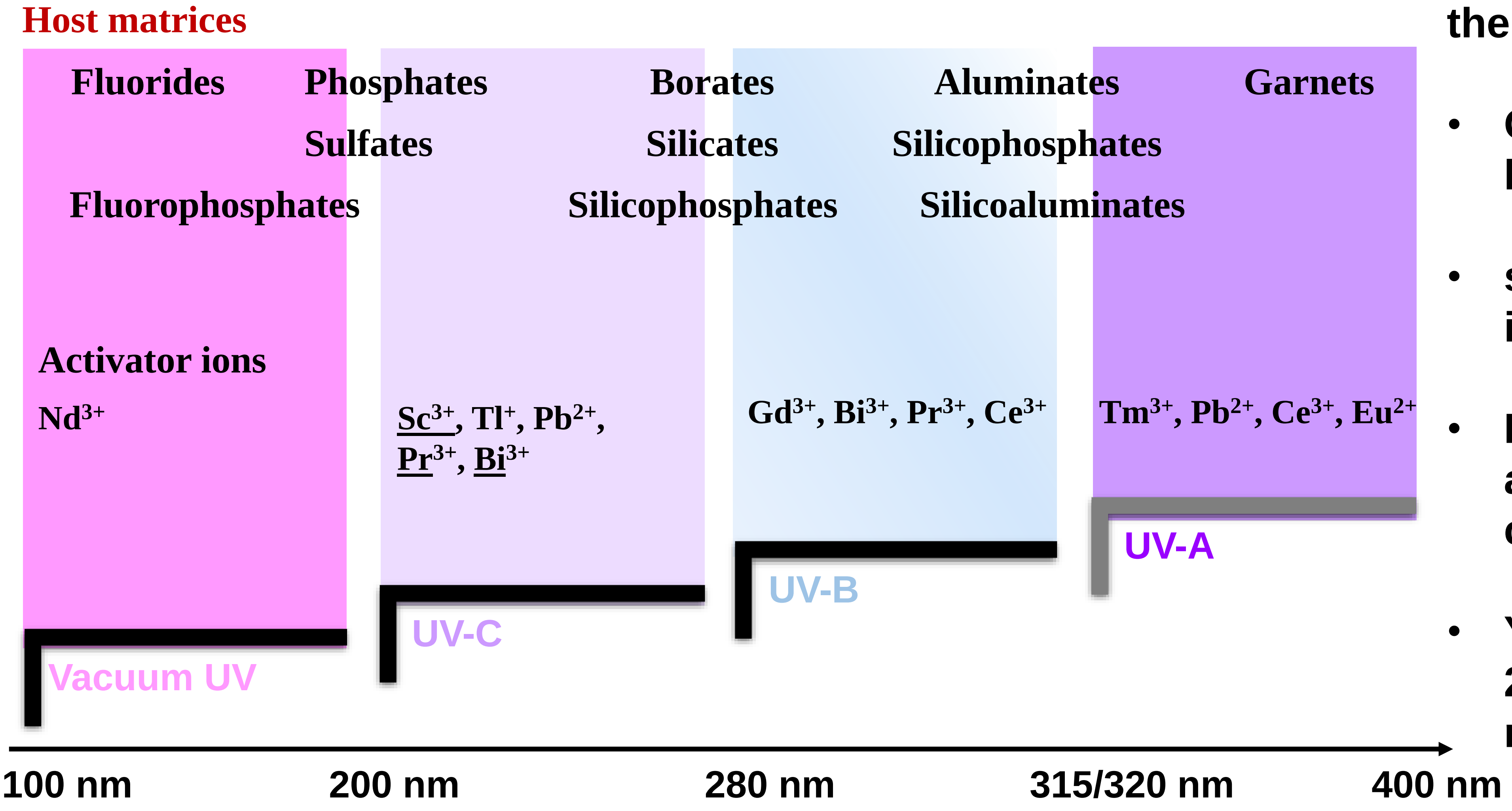
Suitable Host Matrices and Activator Ions



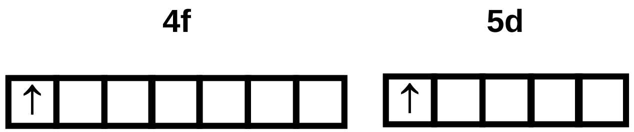
Conclusions due to requirements from the application:

- **Oxidic or fluoridic hosts only**
- **s^2 or trivalent RE ions required**
- **Pr^{3+}, Bi^{3+}, and Sc^{3+} are ROHs compliable**
- **YPO_4:Bi emitting at 241 nm is used a reference converter**

5. Deep UV-C Emitting Converters

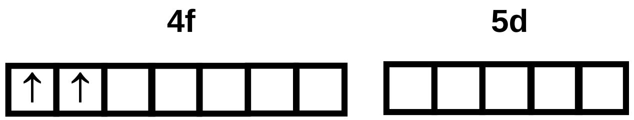
Suitable Host Matrices and Activator Ions

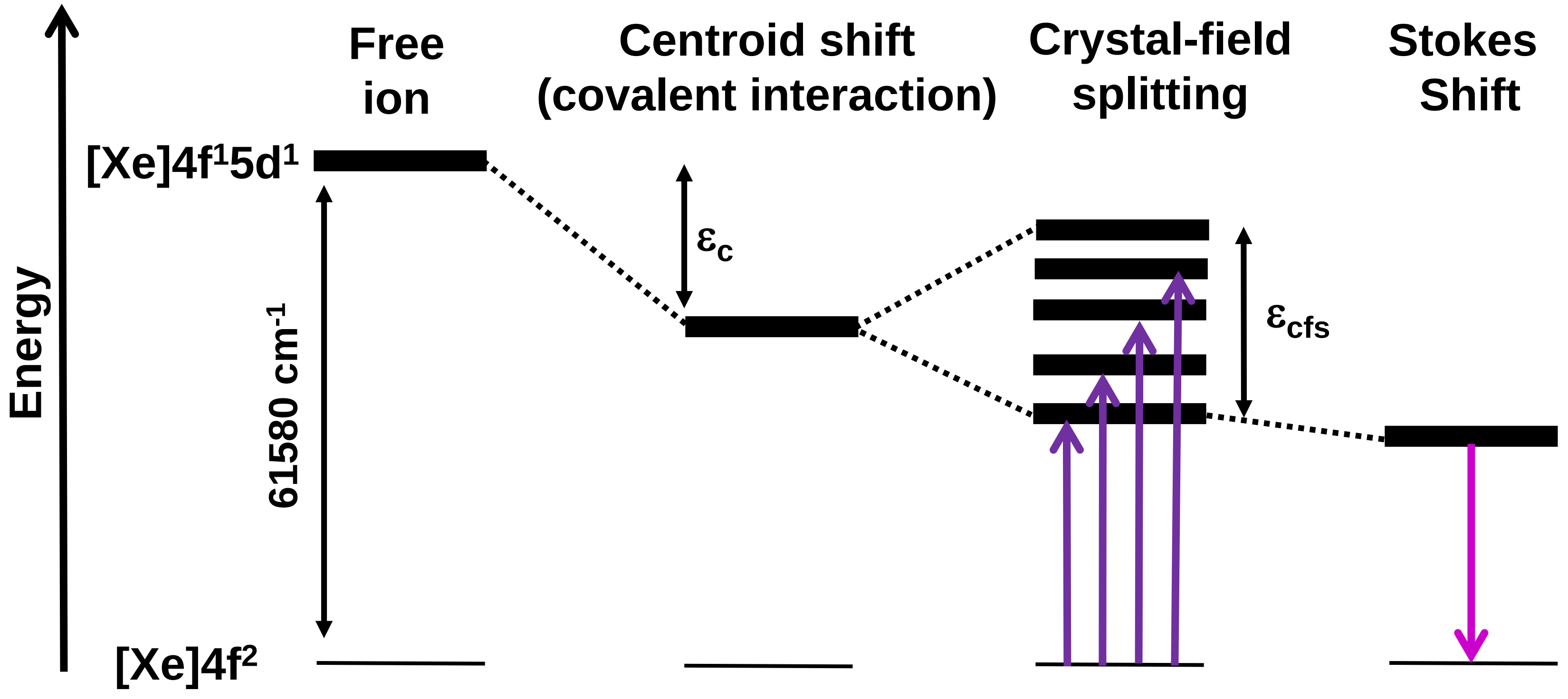
Pr^{3+} excited state



Pr^{3+} ground state

[Xe]4f² → 13 SLJ-States

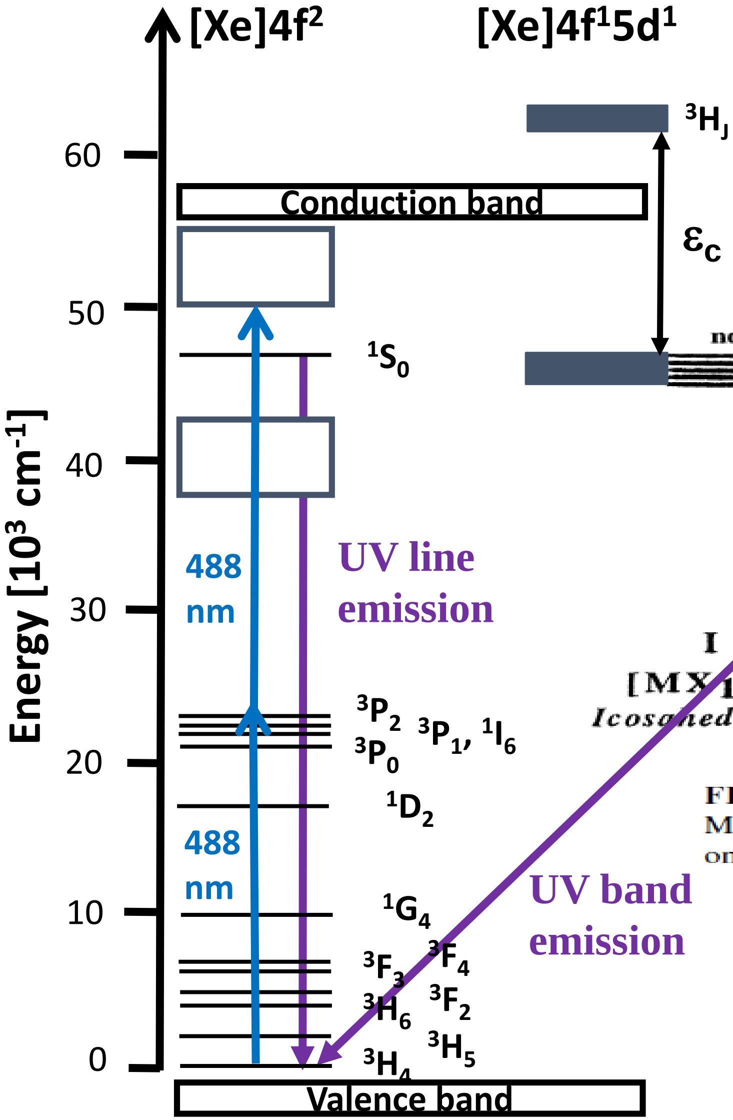




Ion	Eu^{2+}	Ce^{3+}	Pr^{3+}	Nd^{3+}
Energy distance between [Xe]4f² and [Xe]4f¹5d¹ conf.	34000 cm⁻¹ 295 nm	50000 cm⁻¹ 200 nm	61580 cm⁻¹ 160 nm	72000 cm⁻¹ 140 nm

5. Deep UV-C Emitting Converters

Phosphors Activated by Pr^{3+}



----------------- Crystal field (CF) splitting -----------------

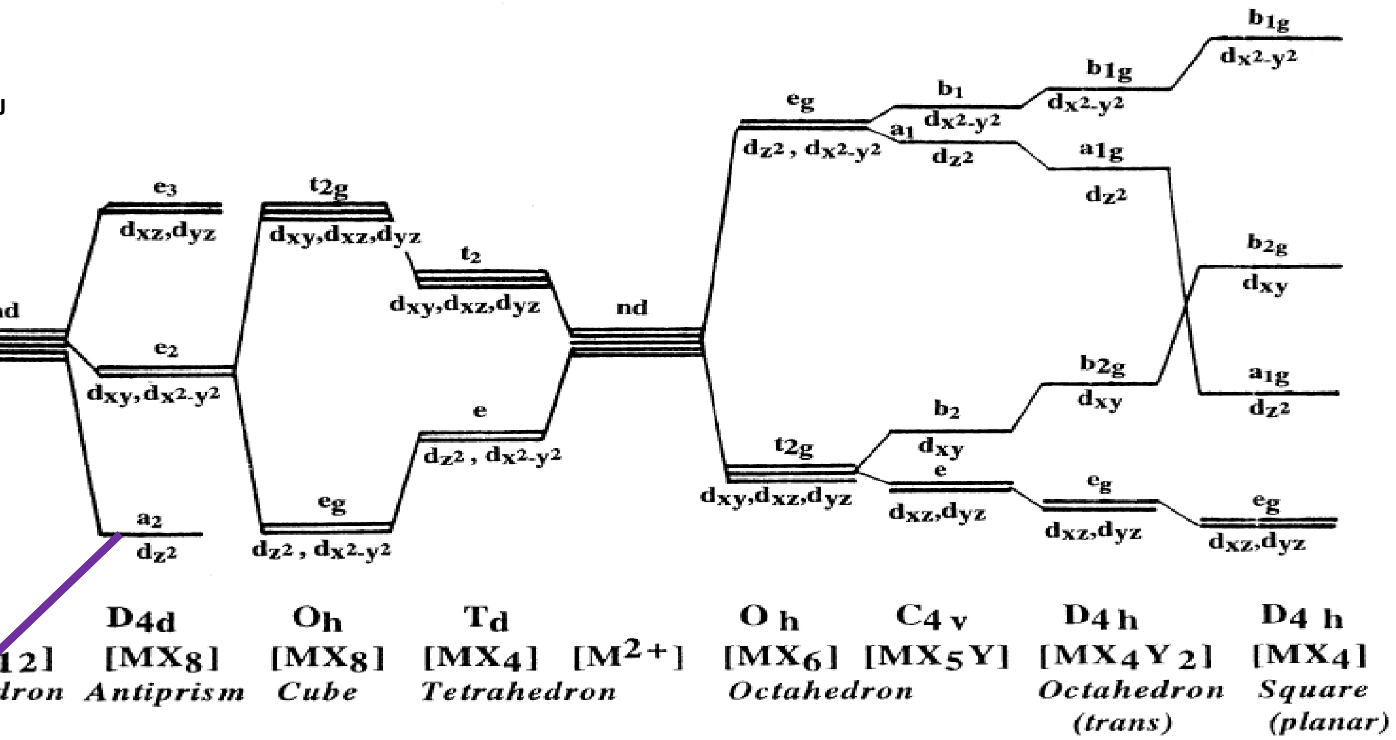


FIGURE 4.5. Splitting of *d* orbital energy levels in ligand fields of different symmetries. In MX_5Y and MX_4Y_2 complexes the splitting of the T_{2g} and E_g terms can be inverted depending on the ratio of field strengths X/Y. (After Schmidtke [4.12].)

Centroid shift and crystal field splitting govern Pr^{3+} emission spectra

⇒ Design of the crystalline environment enables spectral design

5. Deep UV-C Emitting Converters

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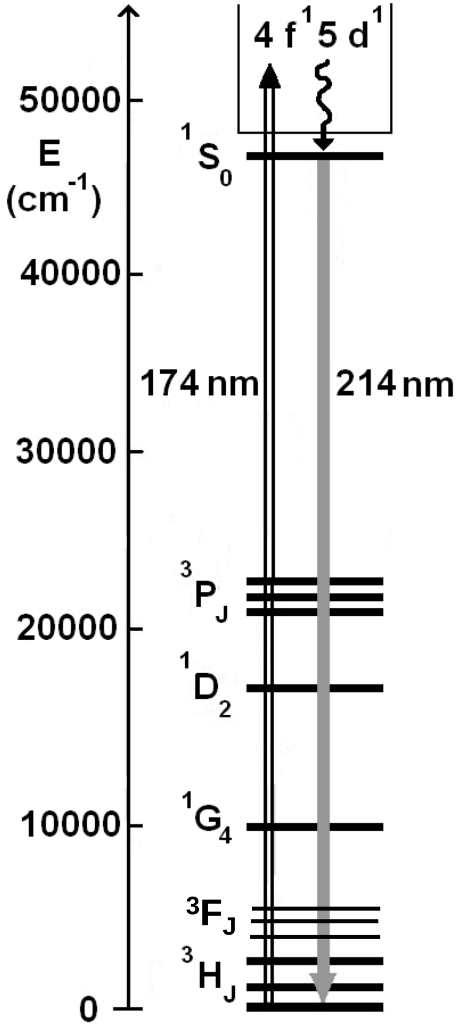
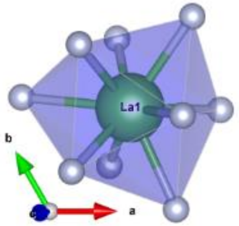
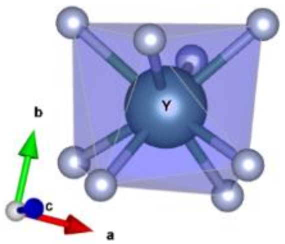
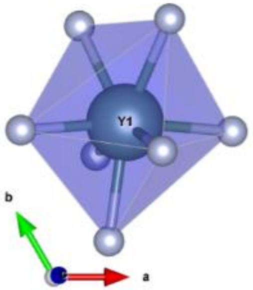
Fluoride Phosphors Activated by Pr^{3+}

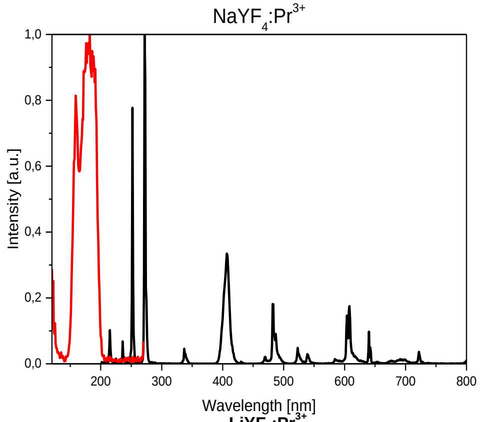


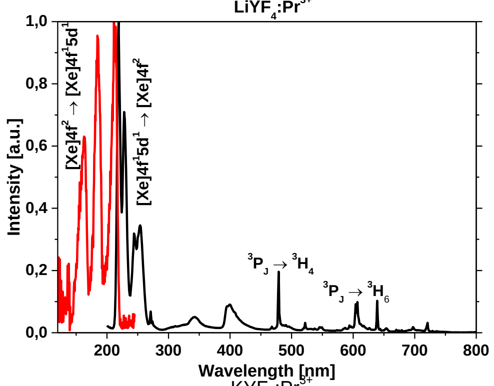
$NaYF_4:Pr^{3+}$	CN 9 (2 sites)	
UV Lines	214 nm + Vis	
$LiYF_4:Pr^{3+}$	CN 8 (1 site)	
UV Bands	218 nm + Vis	
$KYF_4:Pr^{3+}$	CN 7 (6 sites)	
UV Bands	232 nm	

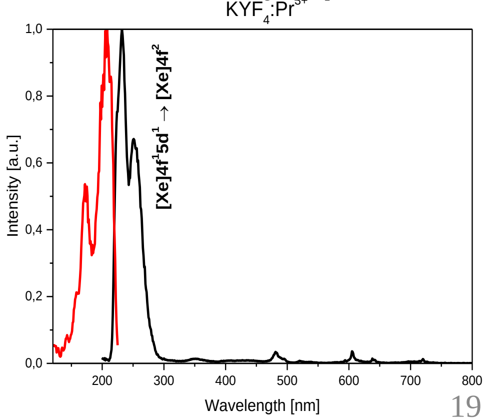












5. Deep UV-C Emitting Converters

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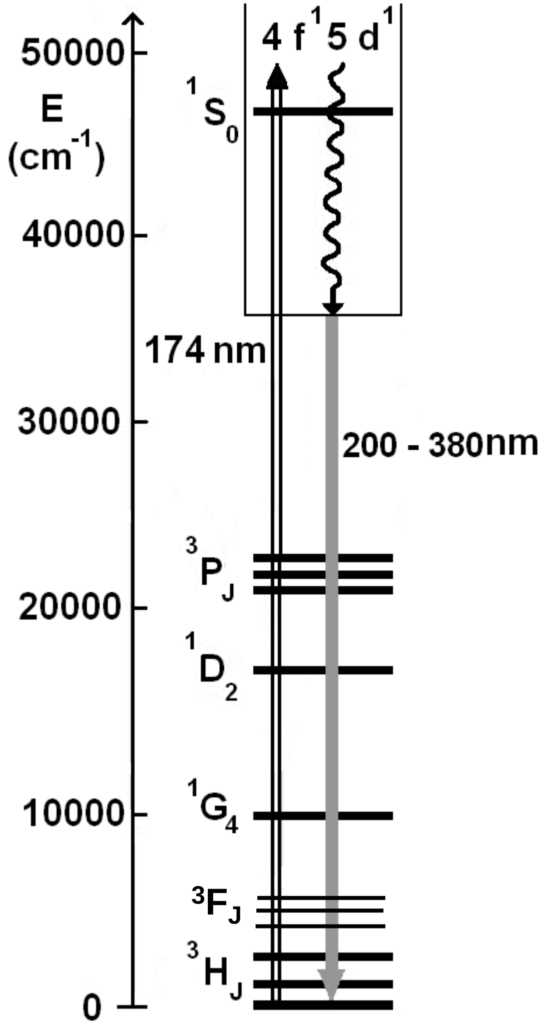
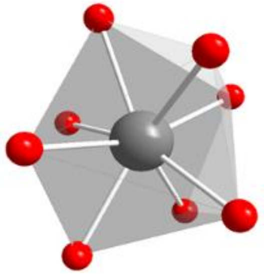
Oxidic Phosphors Activated by Pr^{3+}



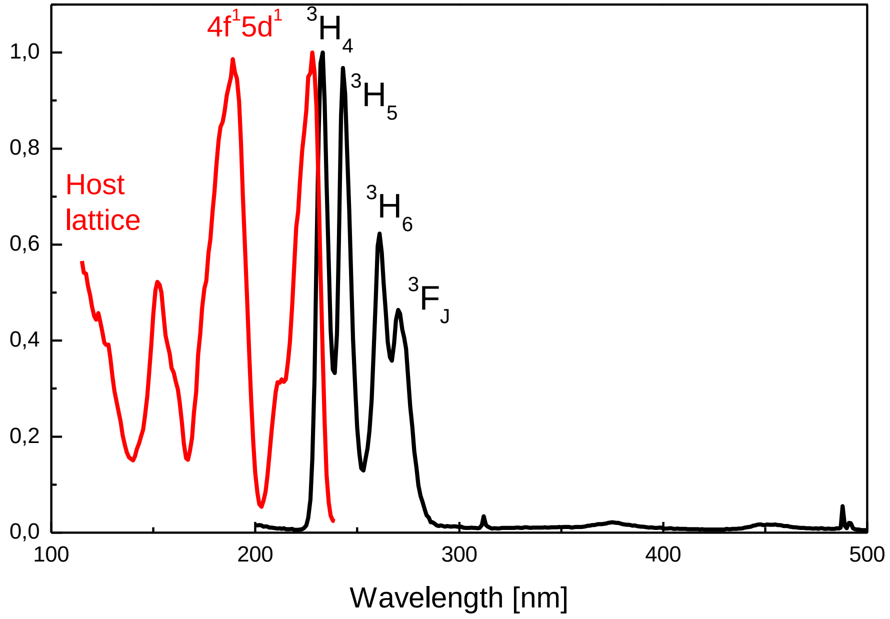
$(Y,Lu)PO_4$
Band gap E_g = 9.0 eV
Single crystallographic site



Distorted dodecahedra CN = 8

Y-O Distances
4 x 2.24 Å
4 x 2.24 Å

CF Splitting ~ 12000 cm^{-1}
Centroid shift ~ 9600 cm^{-1}

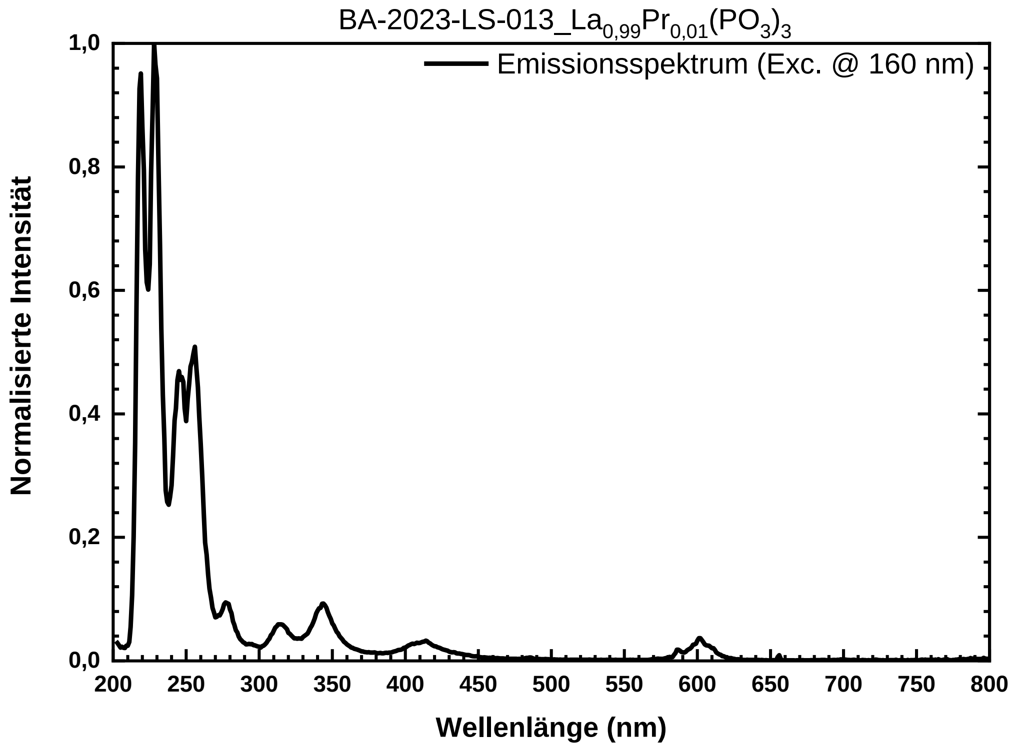


⇒ CF Splitting and centroid shift reduces lowest CF component of the $[Xe]4f^15d^1$ configuration by around 22000 cm^{-1}
⇒ $E(4f^15d^1) < E(^1S_0)$
⇒ $[Xe]4f^15d^1$ - $[Xe]4f^2$ band emission

5. Deep UV-C Emitting Converters

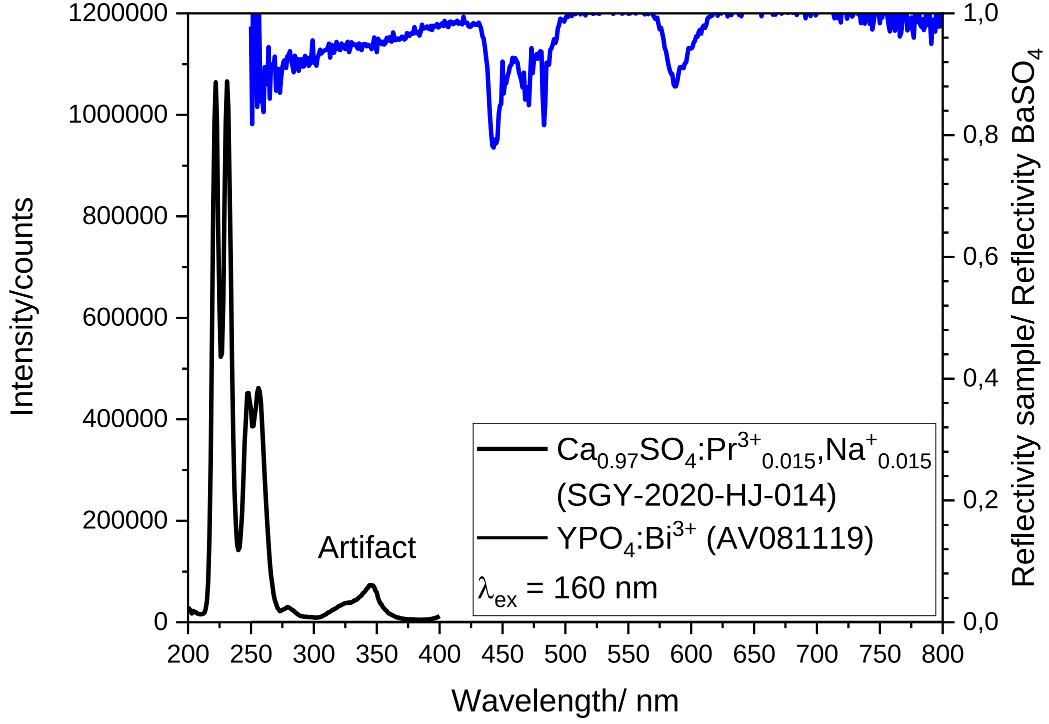
Oxidic Phosphors Activated by Pr^{3+} with Deep UV-C Emission: Enhance Host Acidity!

$La(PO_3)_3:Pr^{3+}$



First emission maxima at 218 nm

$CaSO_4:Pr^{3+}Na^+$



First emission maximum at 222 nm

5. Deep UV-C Emitting Converters

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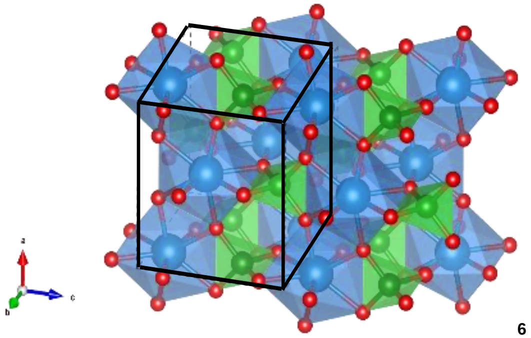
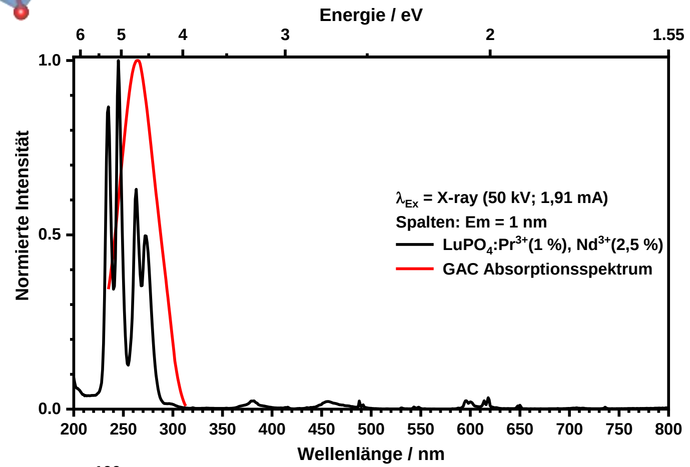
Deep UV-C Phosphors Activated by Pr^{3+}

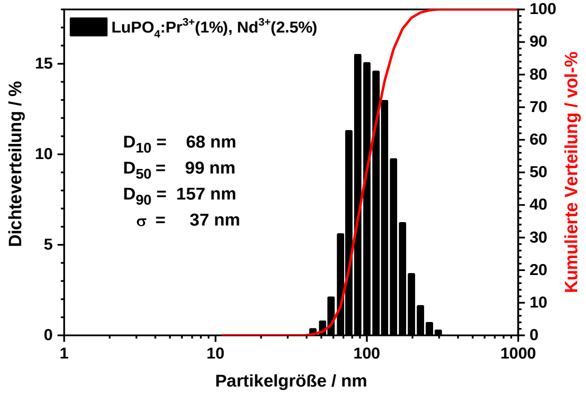
Accessible UV wavelength range 218 – 320 nm

- $LiYF_4$:Pr 218 nm
- $La(PO_3)_3$:Pr 218 nm
- $CaSO_4$:Pr 222 nm
- $LuPO_4$:Pr 232 nm
- YPO_4:Pr 235 nm
- $YAlO_3$:Pr 241 nm
- $CaLi_2SiO_4$:Pr 252 nm
- YBO_3:Pr 265 nm
- $LiYSiO_4$:Pr 267 nm
- Y_2SiO_5:Pr 270 nm
- $Y_2Si_2O_7$:Pr 275 nm
- $Lu_3Ga_2Al_3O_{12}$:Pr 300 nm
- $Lu_3Al_5O_{12}$:Pr 310 nm
- $Y_3Al_5O_{12}$:Pr 320 nm

Structure, emission, and PSD of $LuPO_4$:Pr







5. Deep UV-C Emitting Converters

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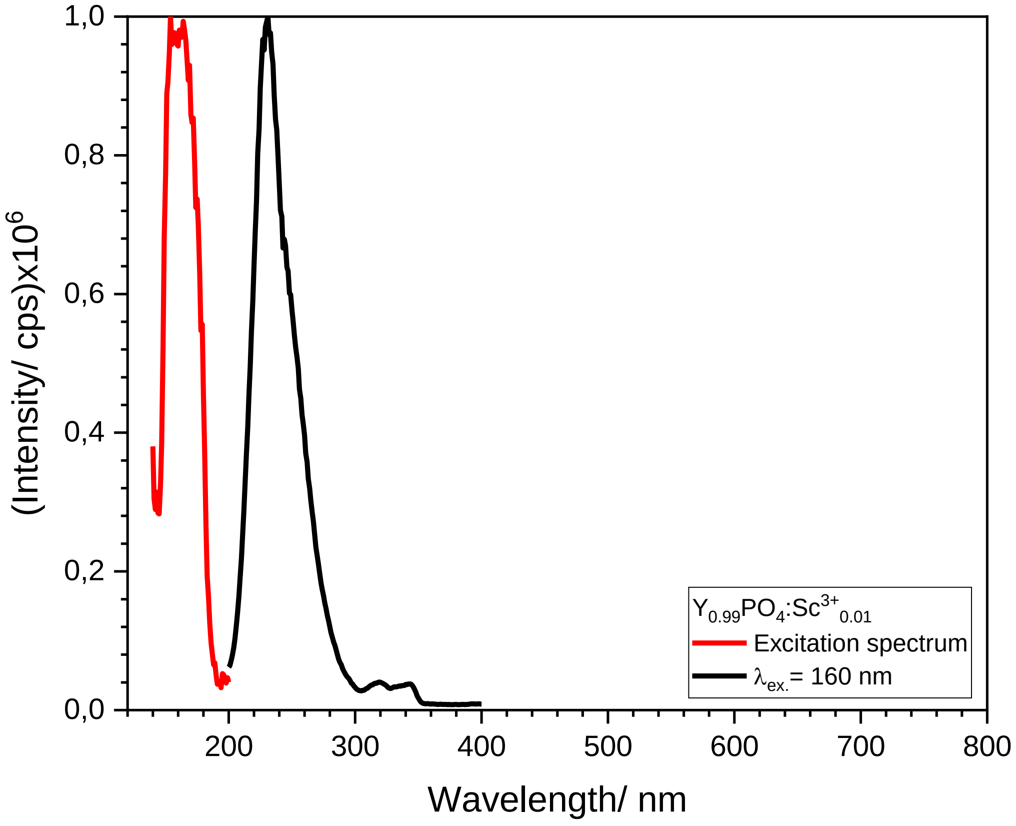
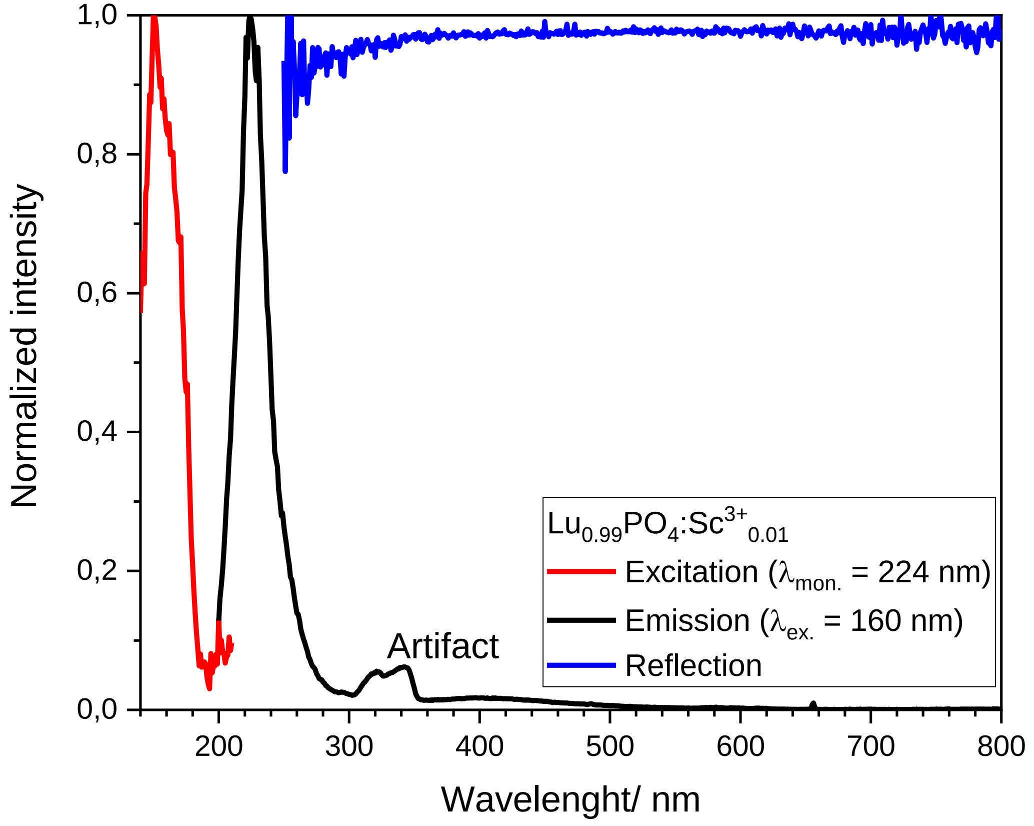
Deep UV-C Emitting Phosphate Phosphors Activated by Sc^{3+}

$YPO_4:Sc^{3+}$



Emission maximum at 230 nm

$LuPO_4:Sc^{3+}$



Emission maximum at 225 nm

5. Deep UV-C Emitting Converters

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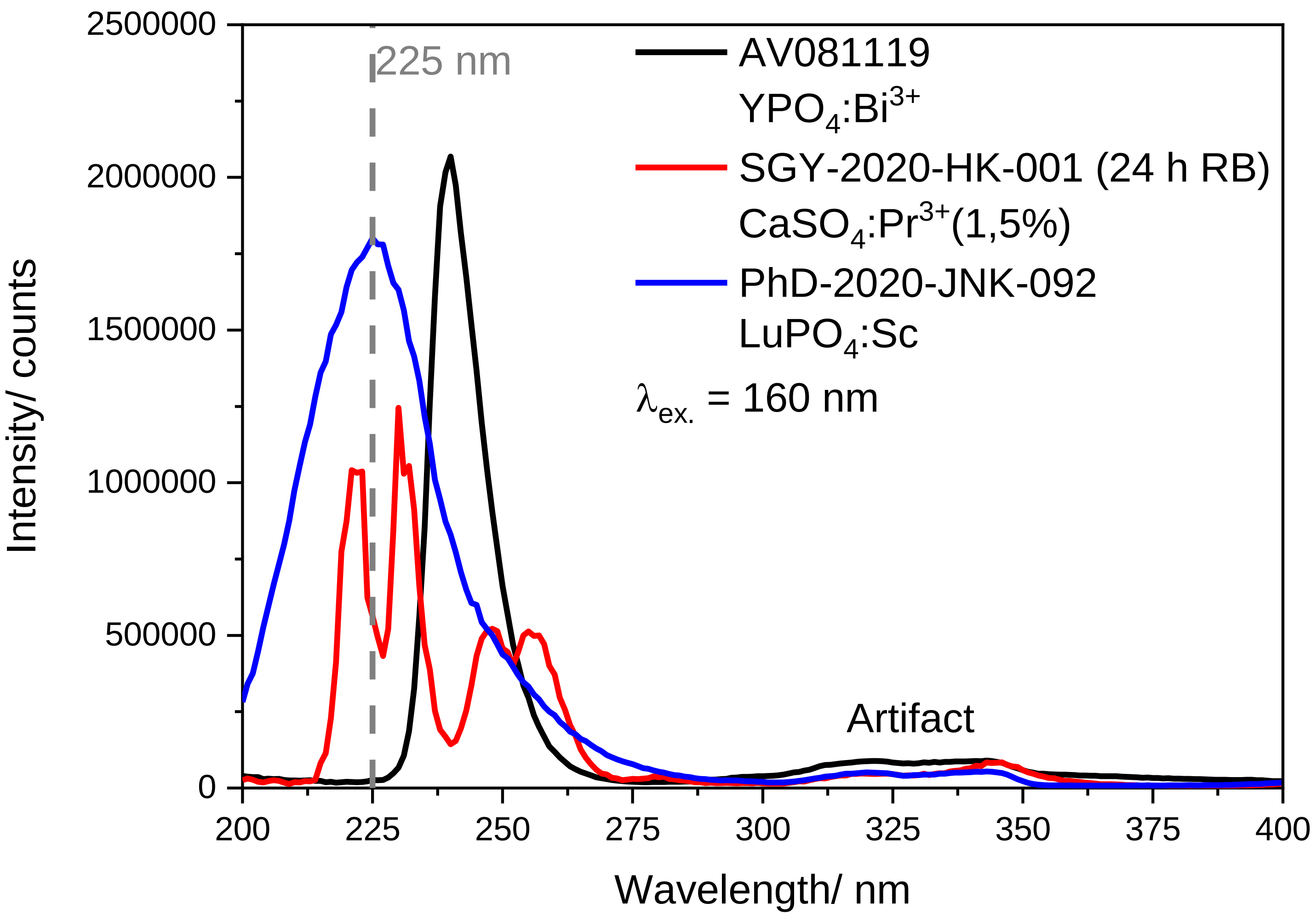
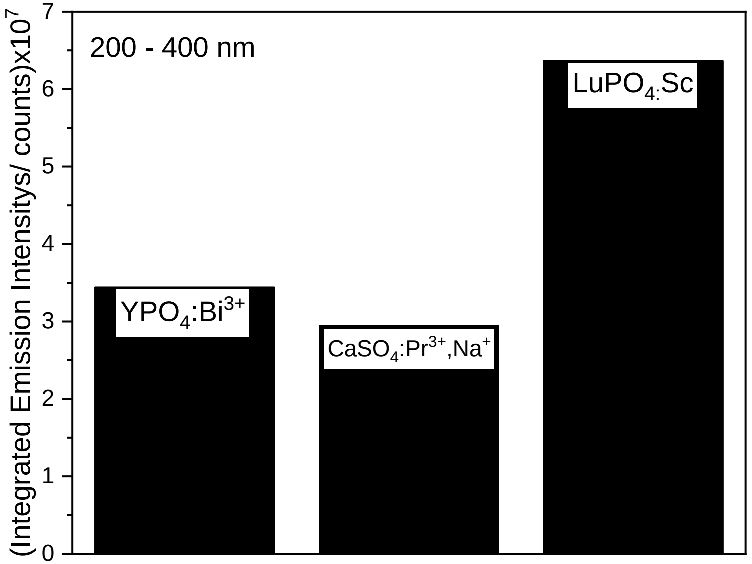
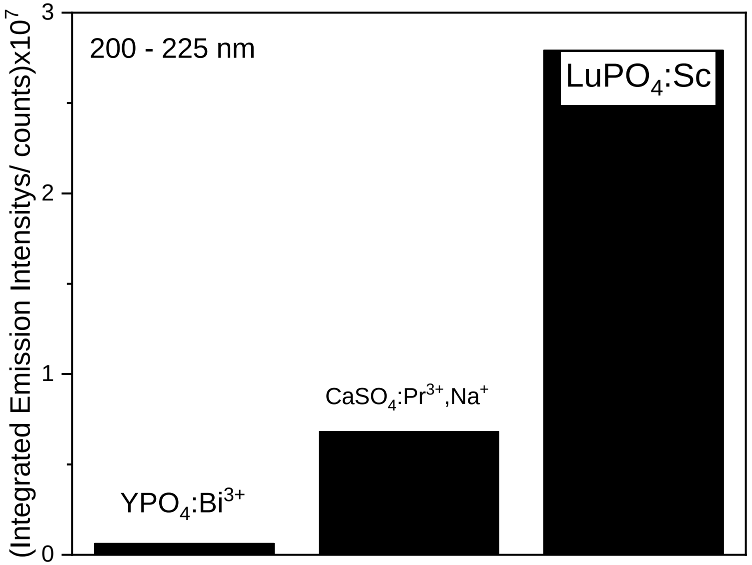
Deep UV-C Emitting Phosphate Phosphors Activated by Sc^{3+}







5. Deep UV-C Emitting up-Converters

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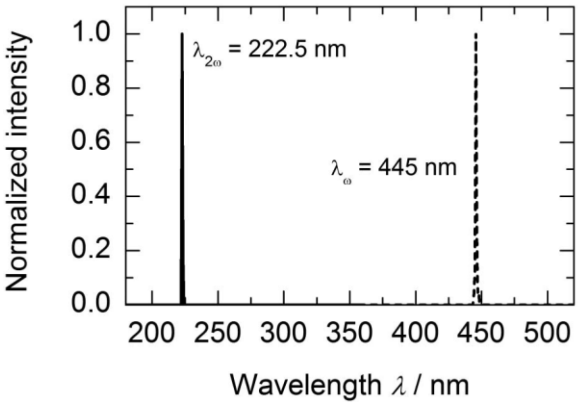
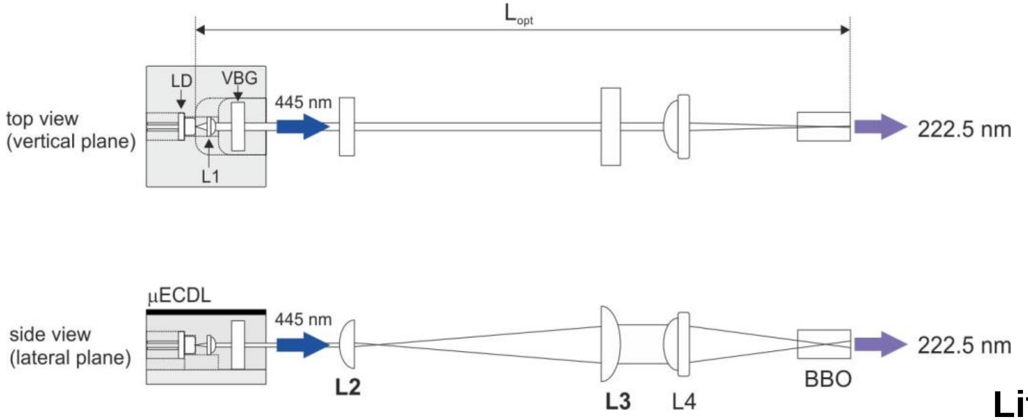
Surface Disinfection Claimed by Blue LED or Laser Diode + Blue-to-UV up-Converter

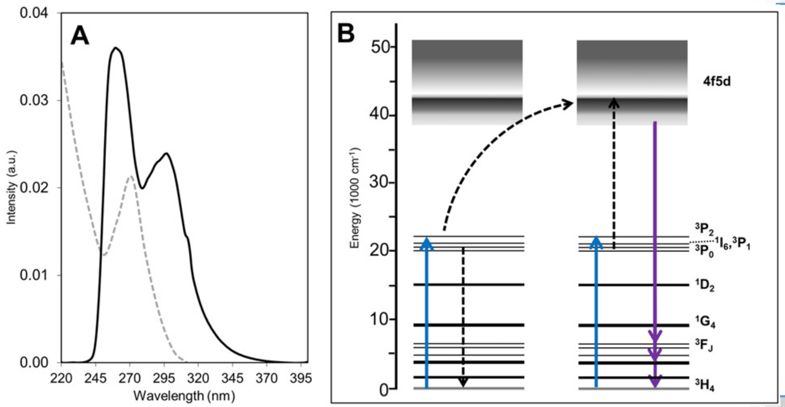
1. SHG: 445 nm laser diode + ß-BaB_2O_4 NLO crystal, Germany, Berlin

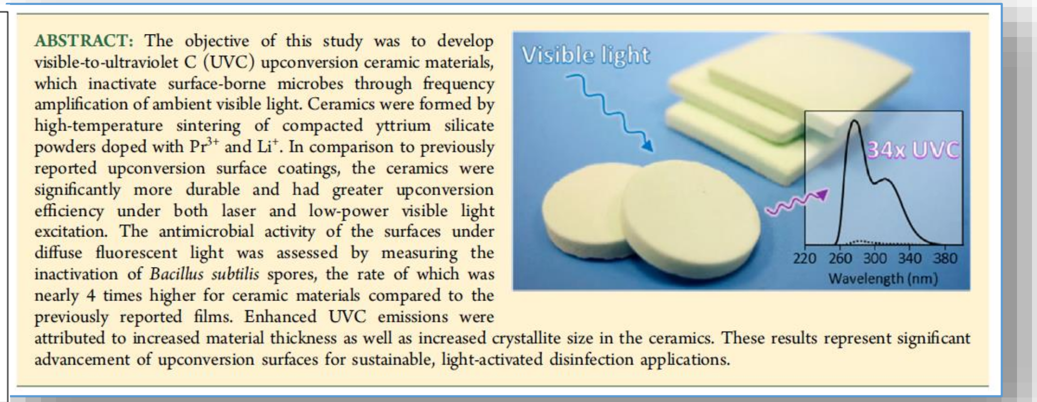




Lit.: G. Tränkle et al., IEEE Phot. Tech. Lett. 30 (2018) 289

2. ETU: 445 nm laser diode + Y_2SiO_5:Pr,Li ceramic, Georgia, Atlanta





ABSTRACT: The objective of this study was to develop visible-to-ultraviolet C (UVC) upconversion ceramic materials, which inactivate surface-borne microbes through frequency amplification of ambient visible light. Ceramics were formed by high-temperature sintering of compacted yttrium silicate powders doped with Pr^{3+} and Li^+. In comparison to previously reported upconversion surface coatings, the ceramics were significantly more durable and had greater upconversion efficiency under both laser and low-power visible light excitation. The antimicrobial activity of the surfaces under diffuse fluorescent light was assessed by measuring the inactivation of *Bacillus subtilis* spores, the rate of which was nearly 4 times higher for ceramic materials compared to the previously reported films. Enhanced UVC emissions were attributed to increased material thickness as well as increased crystallite size in the ceramics. These results represent significant advancement of upconversion surfaces for sustainable, light-activated disinfection applications.

Lit.:
1. E.L. Cates, A.P. Wilkinson, J.-H. Kim, J. Luminescence 160 (2015) 202
2. E.L. Cates, J.-H. Kim, J. Photochemistry & Photobiology, B: Biology 153 (2015) 405

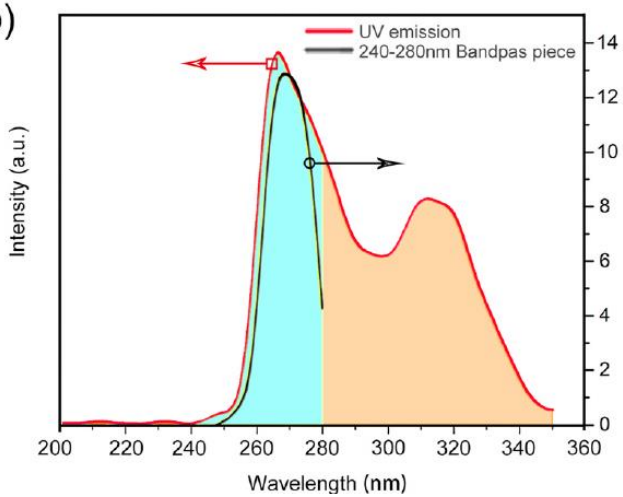
5. Deep UV-C Emitting up-Converters

Surface Disinfection by Blue LED or Laser Diode + Blue-to-UV up-Converter

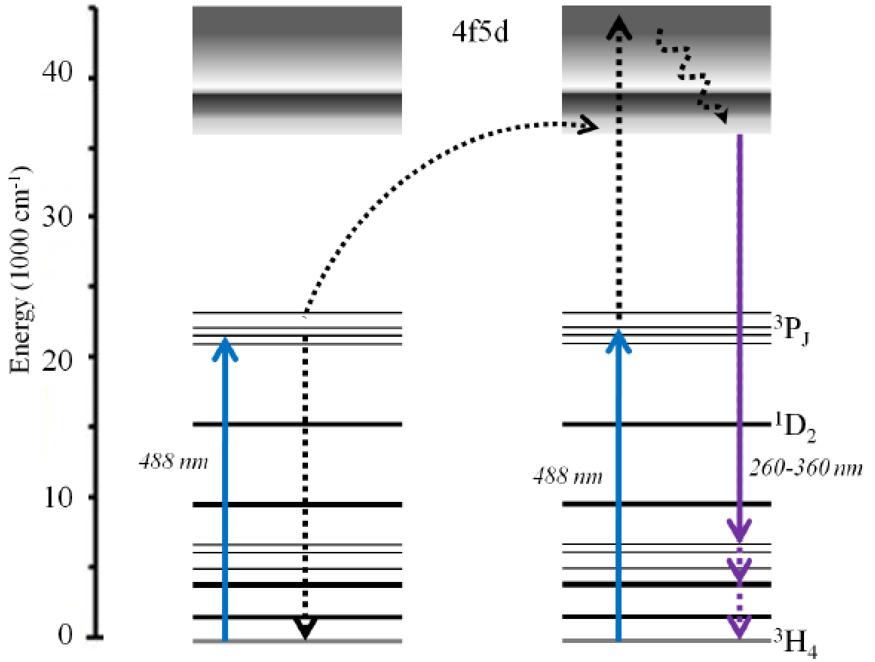
Some published UV up-Converter b)

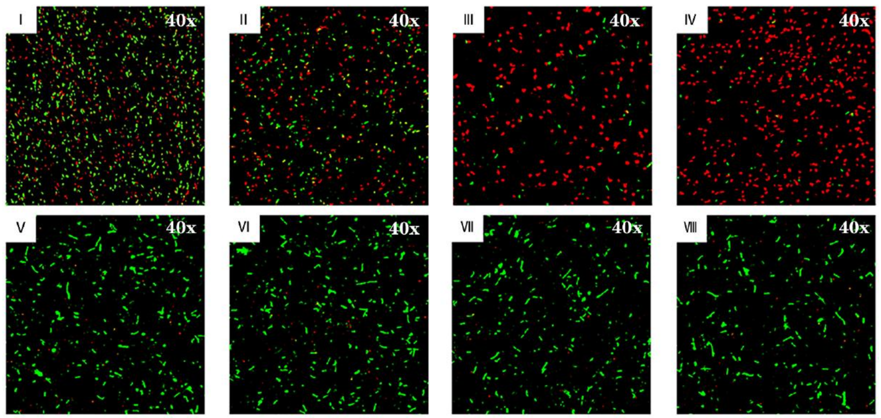
- Y_2SiO_5:Pr,Li
- $SrLi_2SiO_4$:Pr
- $CaLi_2SiO_4$:Pr
- $Lu_3Al_5O_{12}$:Pr

Sole working activator: Pr^{3+}



Energy Transfer Up-Conversion





Lit.:
a) Z. Yin, P. Yuan, Z. Zhu, T. Li, Y. Yang, Pr^{3+} doped Li_2SrSiO_4: an efficient visible-ultraviolet C up-conversion phosphor, Ceramics International (2020)
b) T. Jüstel et al. WO002021073914 A1, WO002021073915 A1

5. Deep UV-C Emitting up-Converters

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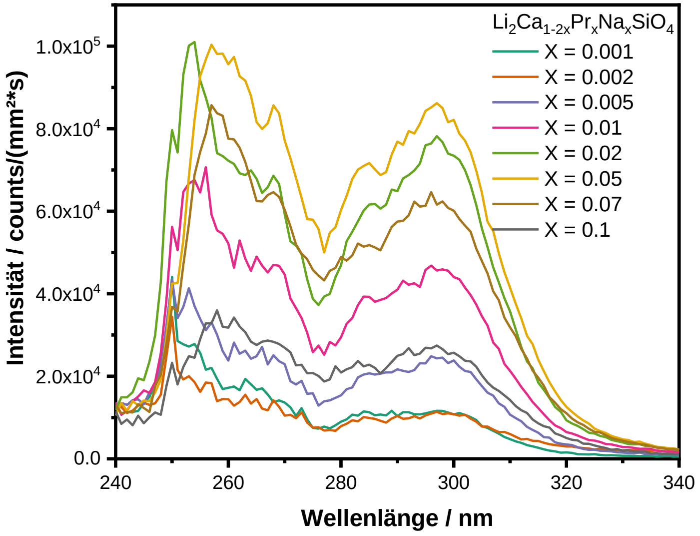
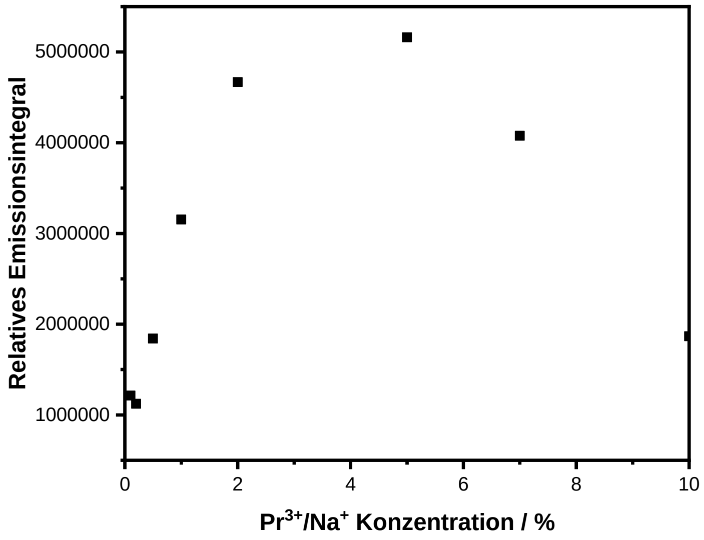
Up-Converter $CaLi_2SiO_4:Pr^{3+}$(%)Na^+(5%)





Reference

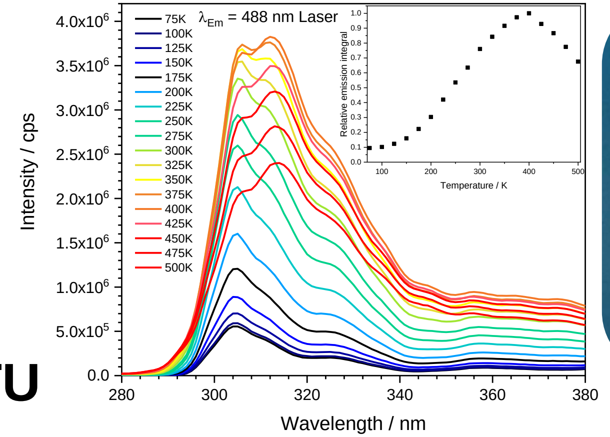
$Lu_3Al_5O_{12}$:Pr

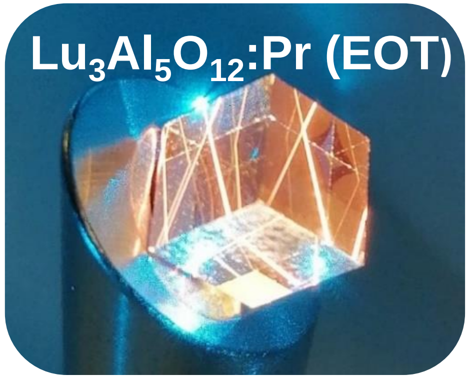
I ~ $4 \cdot 10^6$ cts

QE ~ 0.2%

T_{opt} ~ 400 K

Mechanism: ETU





Host Material for Pr^{3+}	Emission / nm	Excitation / nm
Ba_2SiO_4	250-360	488 nm
$BaY_2Si_3O_{10}$	255-360	488 nm
$Ca_2LuSc_2GaSi_2O_{12}$	280-400	488 nm
$Ca_2Al_2SiO_7$	255-360	488 nm
$CaLi_2SiO_4$	240-350	488 nm
$Ca_2Sc_2Si_3O_{12}$	298-400	488 nm
$KYSiO_4$	265-400	488 nm
$LiYSiO_4$	255-400	488 nm
$Lu_3Al_5O_{12}$	280-400	488 nm
$Lu_3(Al,Ga)_5O_{12}$	280-400	488 nm
$Lu_3Al_3Sc_2O_{12}$	280-400	488 nm
$Lu_2CaAl_4SiO_{12}$	280-400	488 nm
$Lu_2Si_2O_7$	250-360	488 nm
Lu_2SiO_5	250-360	488 nm
$NaYSiO_4$	255-320	488 nm
$Sr_2MgSi_2O_7$	260-410	488 nm
$Sr_3MgSi_2O_6$	280-410	488 nm
Y_2SiO_5	255-355	488 nm

6. UV-C Filter Materials

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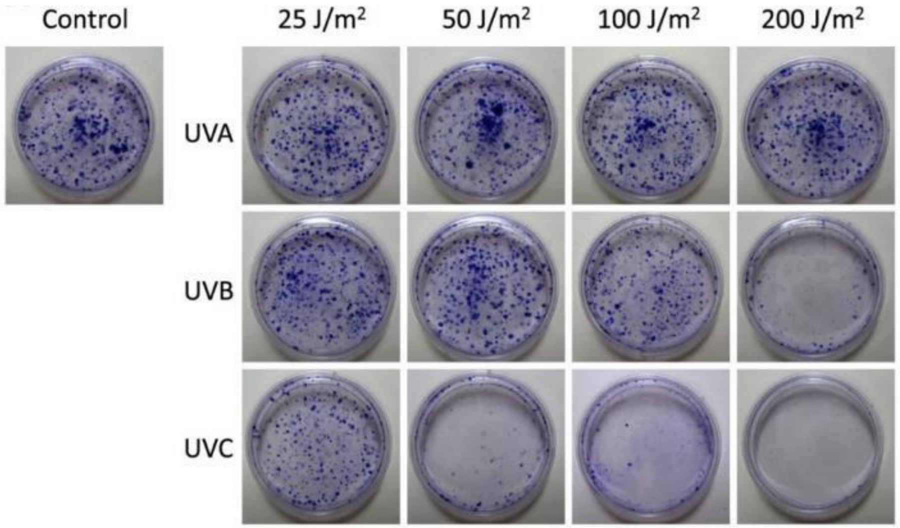
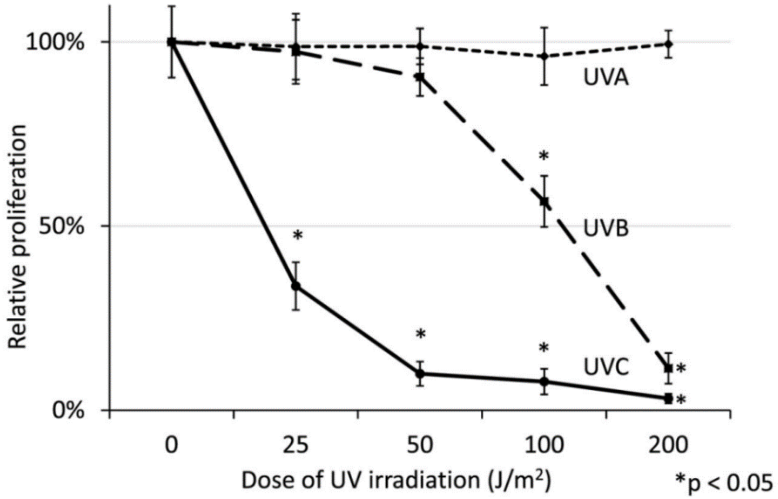
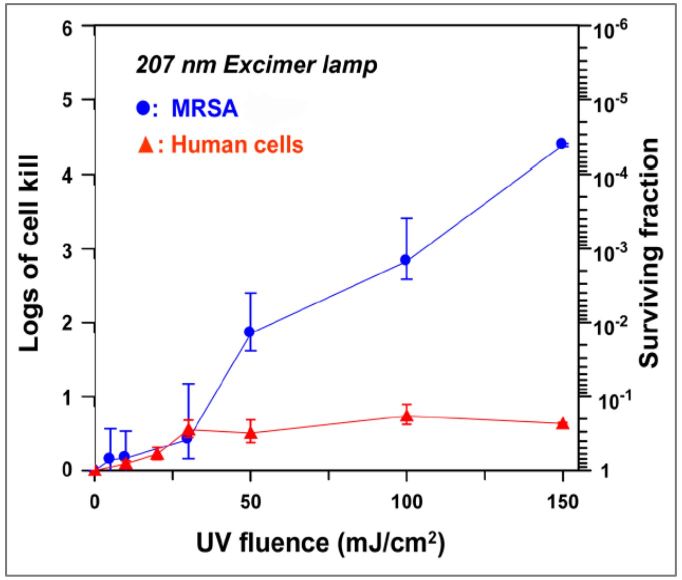
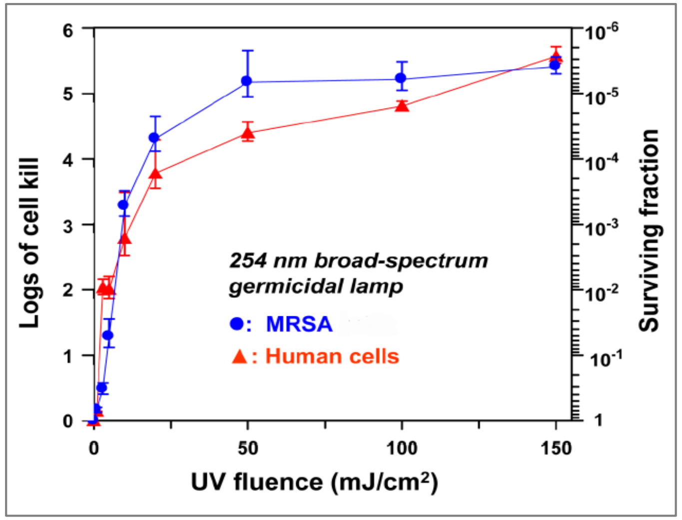
For Indoor Illumination Involving UV-C Radiation









	Penetration characteristic	Damage conferred
UV-C	Penetrates cell membranes/cell walls	mainly DNA damage
UV-B	Most responsible for sunburns. Penetrates deeper than UV-C, but is typically adsorbed by the skin's stratum corneum (dead cell layer)	DNA and other cell components by generation of free radicals
UV-A	Long wavelengths that reach inner strata of skin causing premature aging in humans	Shown to cause membrane damage

increasing penetration

Typical penetration depth of UV-C radiation into tissue ~ 40 µm!

Lit.: S. Miwa et al., J. Cellular Biochemistry 114 (2013) 2493

6. UV-C Filter Materials

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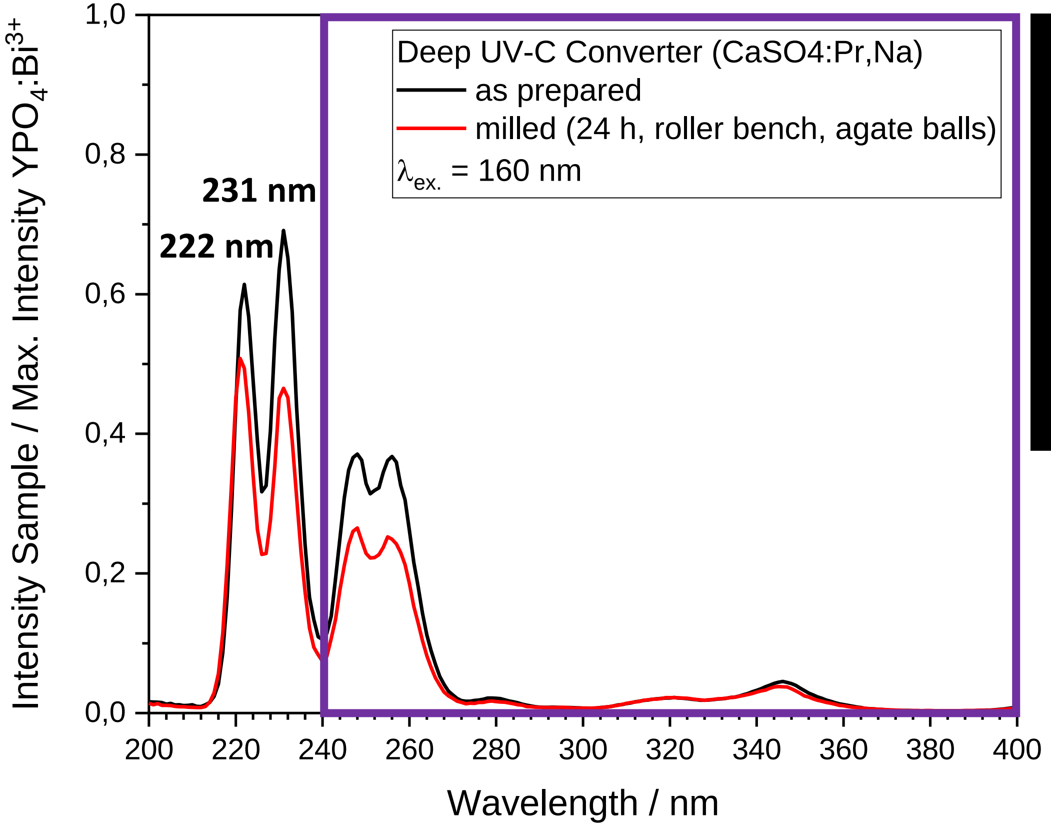
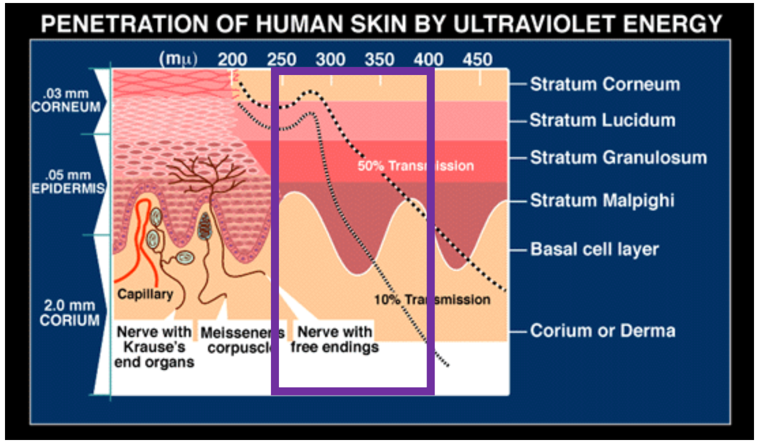
Motivation: Indoor Illumination Involving UV-C Radiation

Idea: Use of Xe_2^* excimer discharge lamps with suitable radiation converter screen (172 nm → 222 nm)

<u>Best practice phosphors</u>

$LiYF_4$:Pr	**218 nm**
$CaSO_4$:Pr	**222 nm**
$LuPO_4$:Pr	**232 nm**





Desired UV filter

Challenge: A filter for 240 – 400 nm radiation is required

6. UV-C Filter Materials

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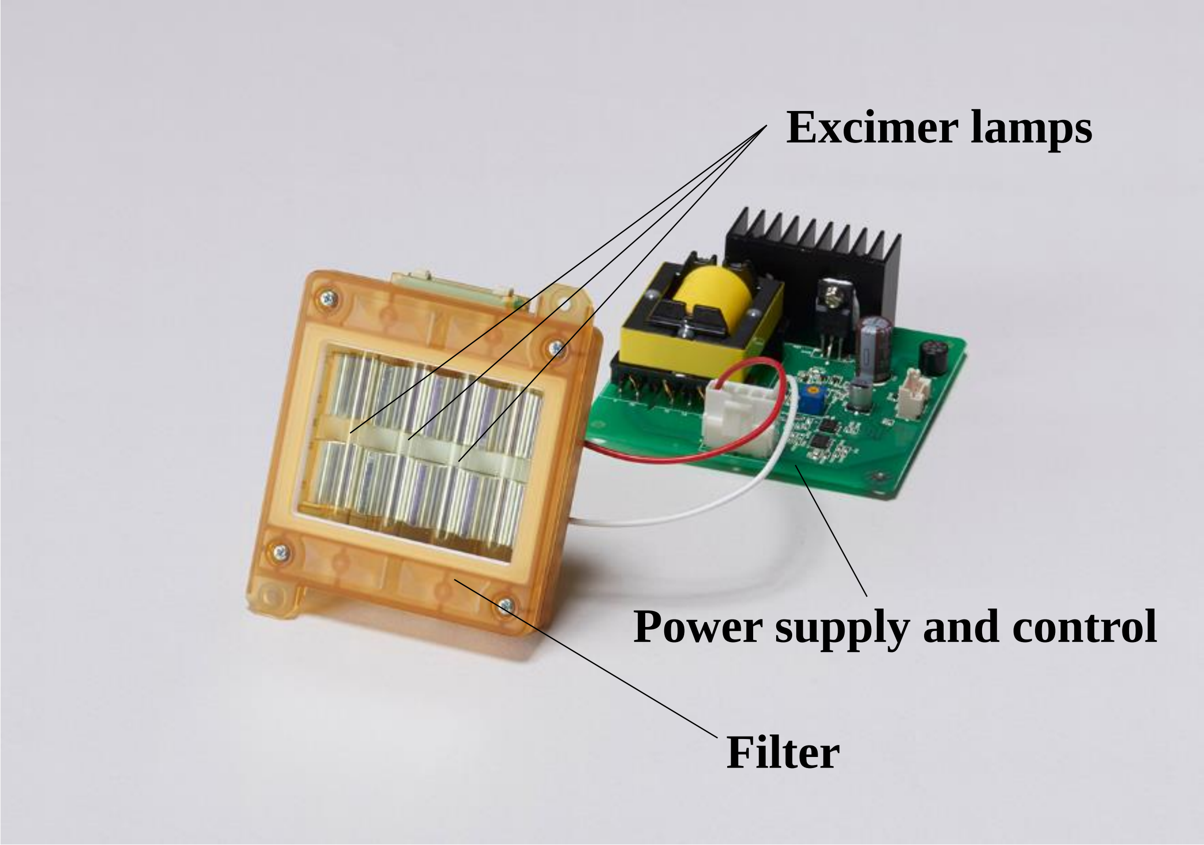
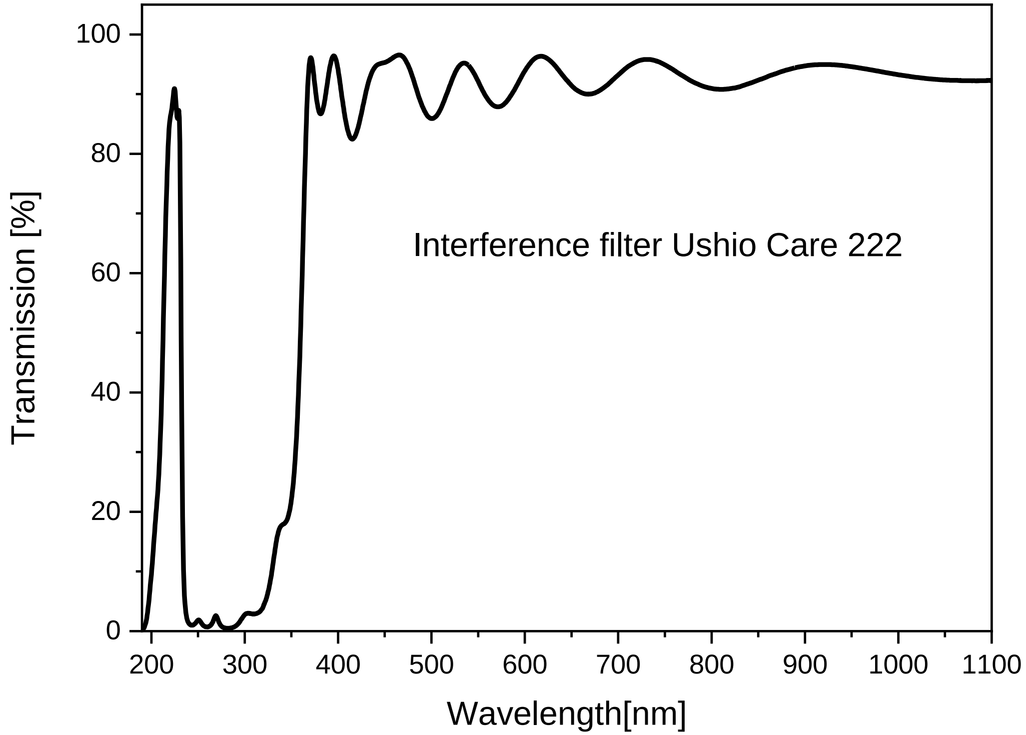
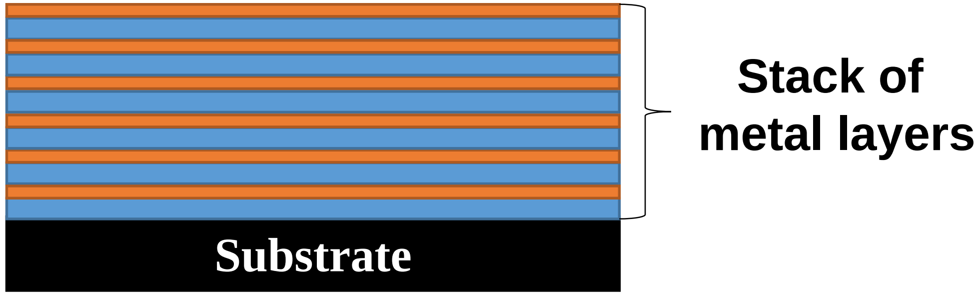
Components of Care222® Ushio





Sketch of the applied interference filter



6. UV-C Filter Materials

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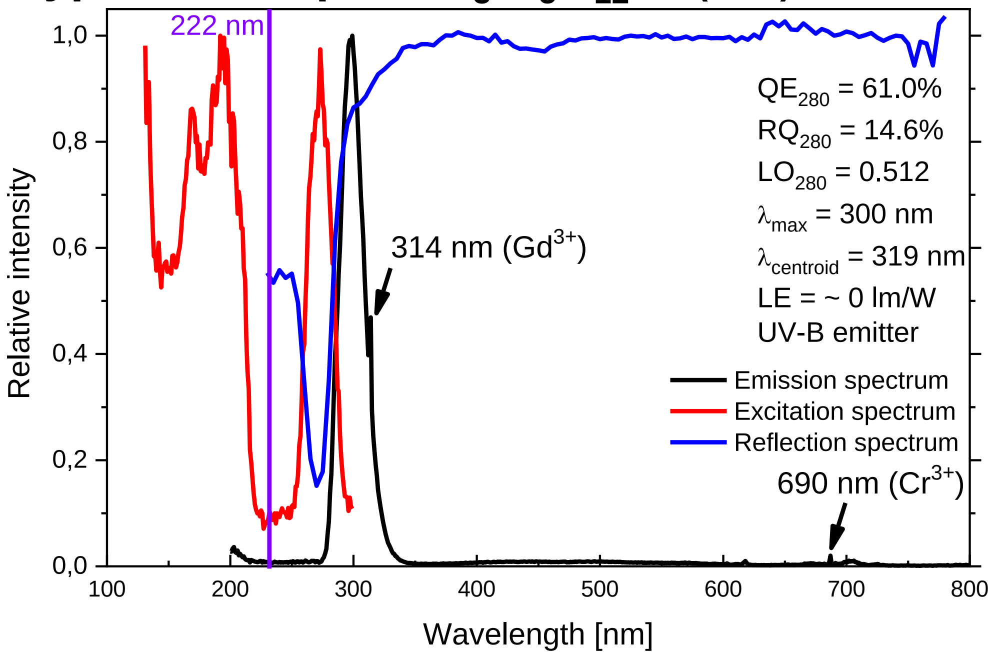
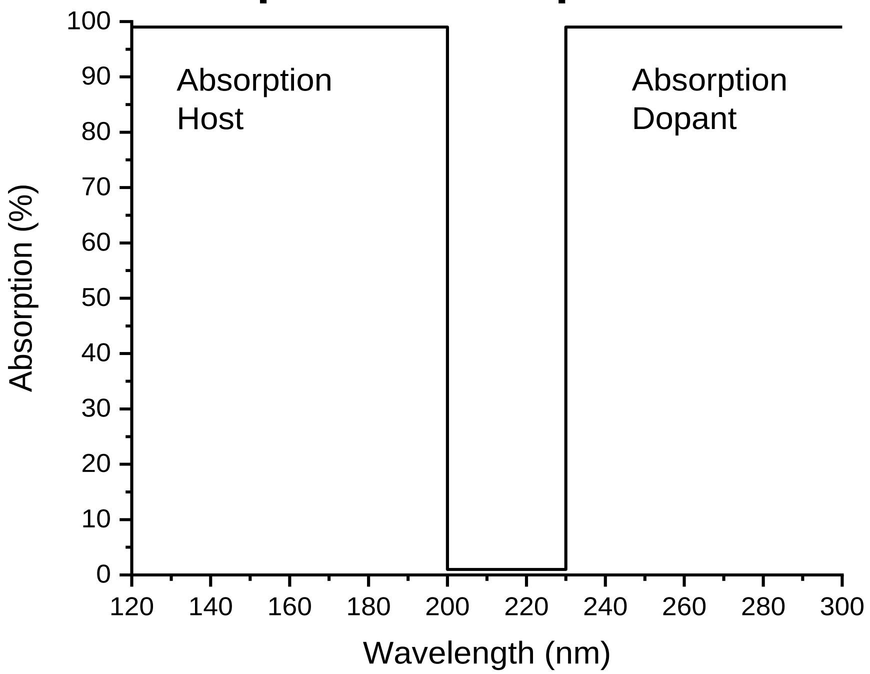
Alternative filter: Absorption pigment with suitable band gap and long edge absorbing dopant

- Host material with absorption edge at 190 to 200 nm (6.2 - 6.4 eV)
- Activator with high absorption cross section between 250 and 300 nm
- s^2-Ion Bi^{3+}: $[Xe]4f^{14}5d^{10}6s^2 \rightarrow [Xe]4f^{14}5d^{10}6s^16p^1$ interconfigurational transition

Typical example: $Lu_3Al_5O_{12}$:Bi(1%) "LuAG:Bi"



Optimal filter spectrum



6. UV-C Filter Materials

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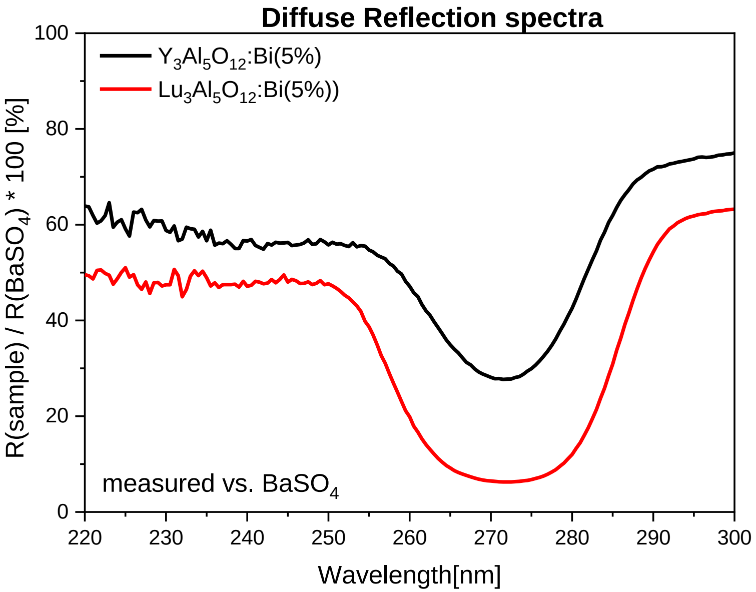
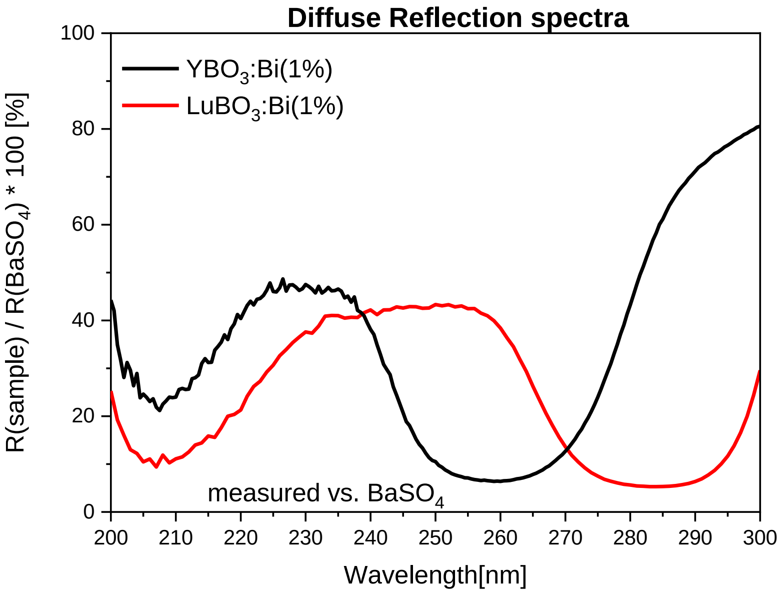
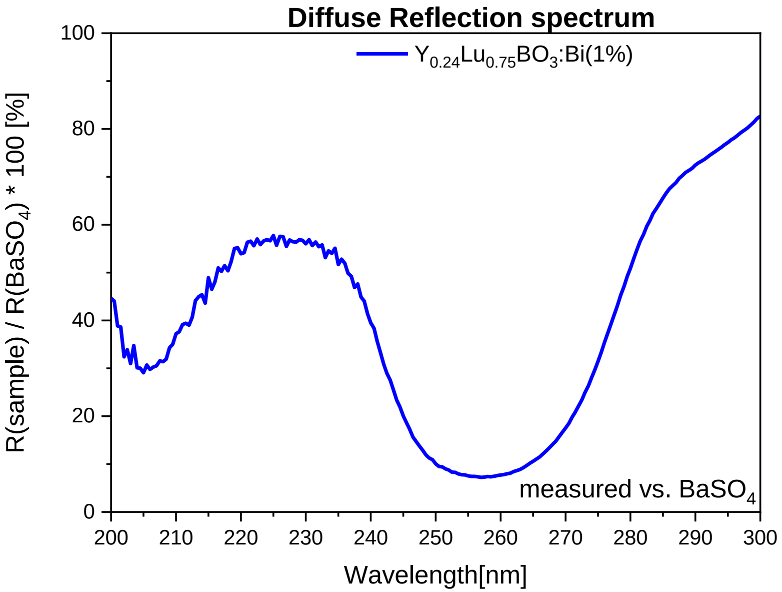
State-of-the-Art: Bi^{3+} Doped ortho-Borates

- **Garnets absorption is too red-shifted and thus not suitable**
- **(Y,Ln)BO_3:Bi^{3+} crystallising in the pseudo-vaterite structure (Ln = Sc, Nd – Lu)**
- **(Lu,Ln)BO_3:Bi^{3+} crystallising in the calcite structure are not suitable**







6. UV-C Filter Materials

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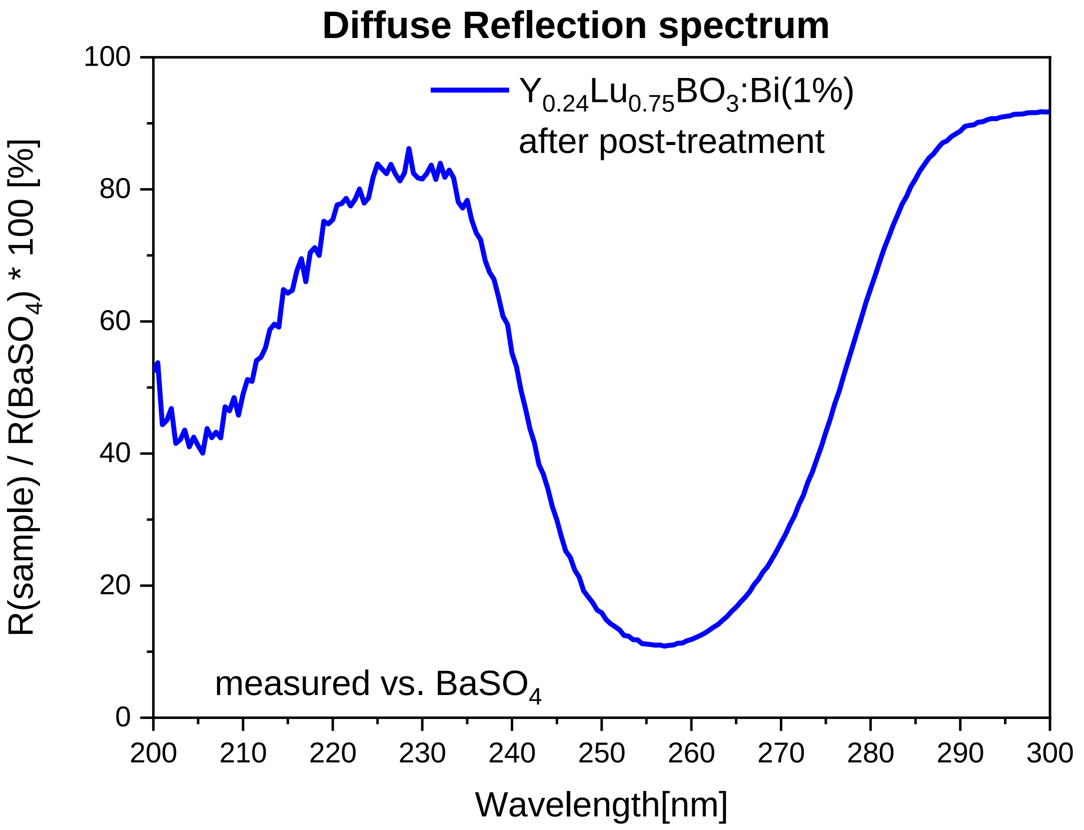
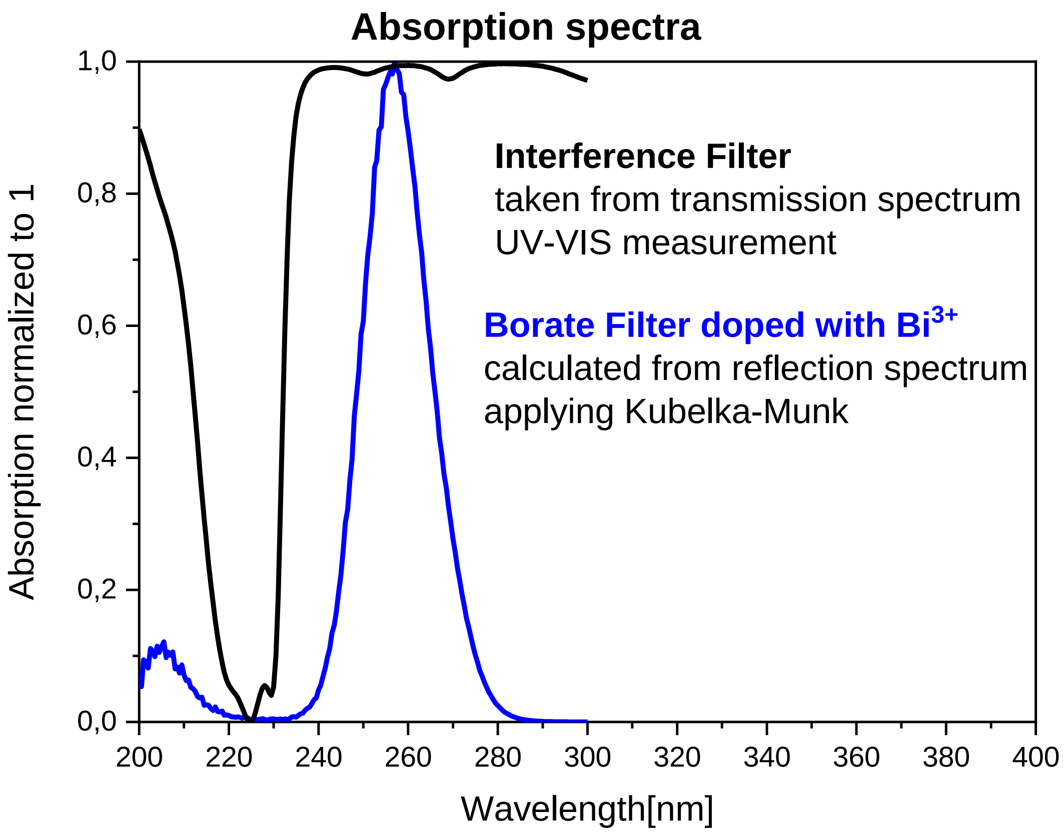
Optimisation of (Y,Lu)BO_3 Doped with Bi^{3+}

Reflectance could be increased by the application of a post-treatment, viz. a washing process

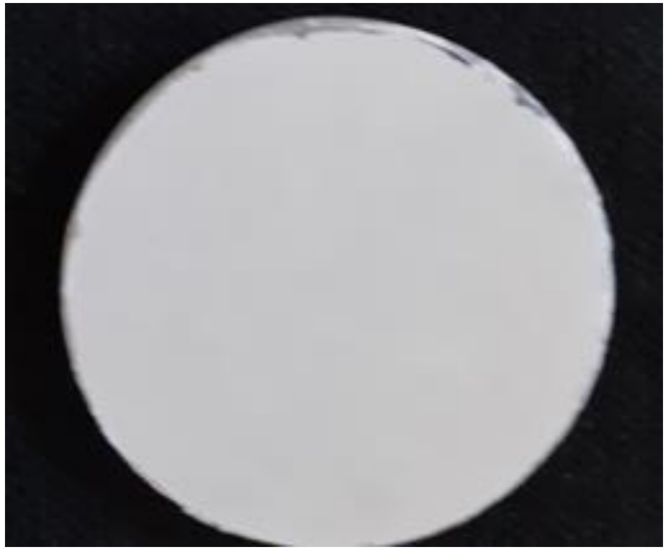




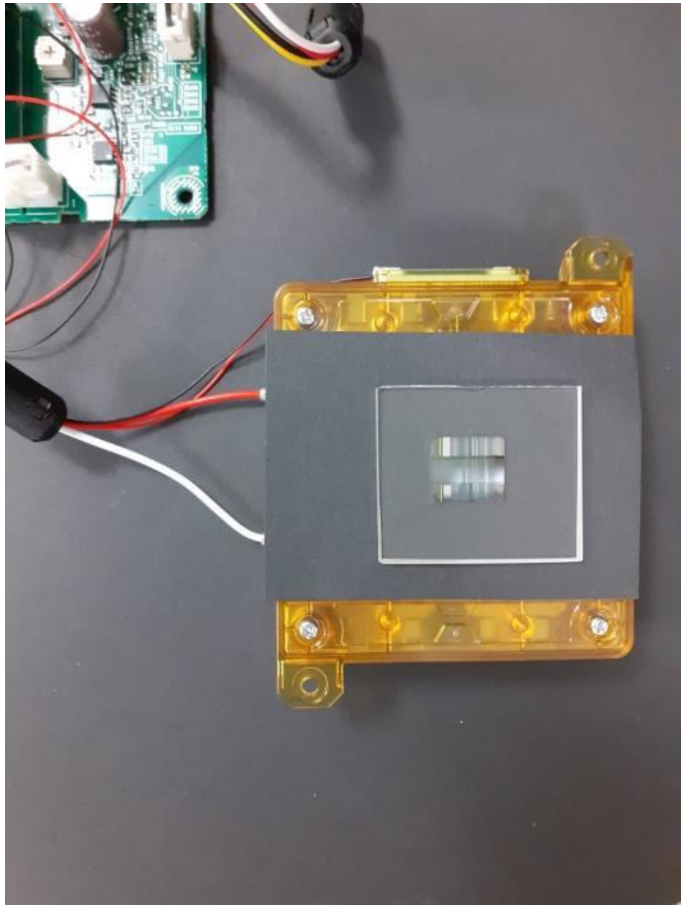
6. UV-C Filter Materials

Application of $(Y,Lu)BO_3$ Doped with Bi^{3+}

Coated quartz slides were used for spectroscopic characterisation



Finished Coating



- **For transmission spectroscopy, the interference filter was removed from a Ushio Care 222 lamp**
- **The lamp was covered by a black piece of polycarbonate (PC)**
- **The sample was placed on top of the PC**

6. UV-C Filter Materials

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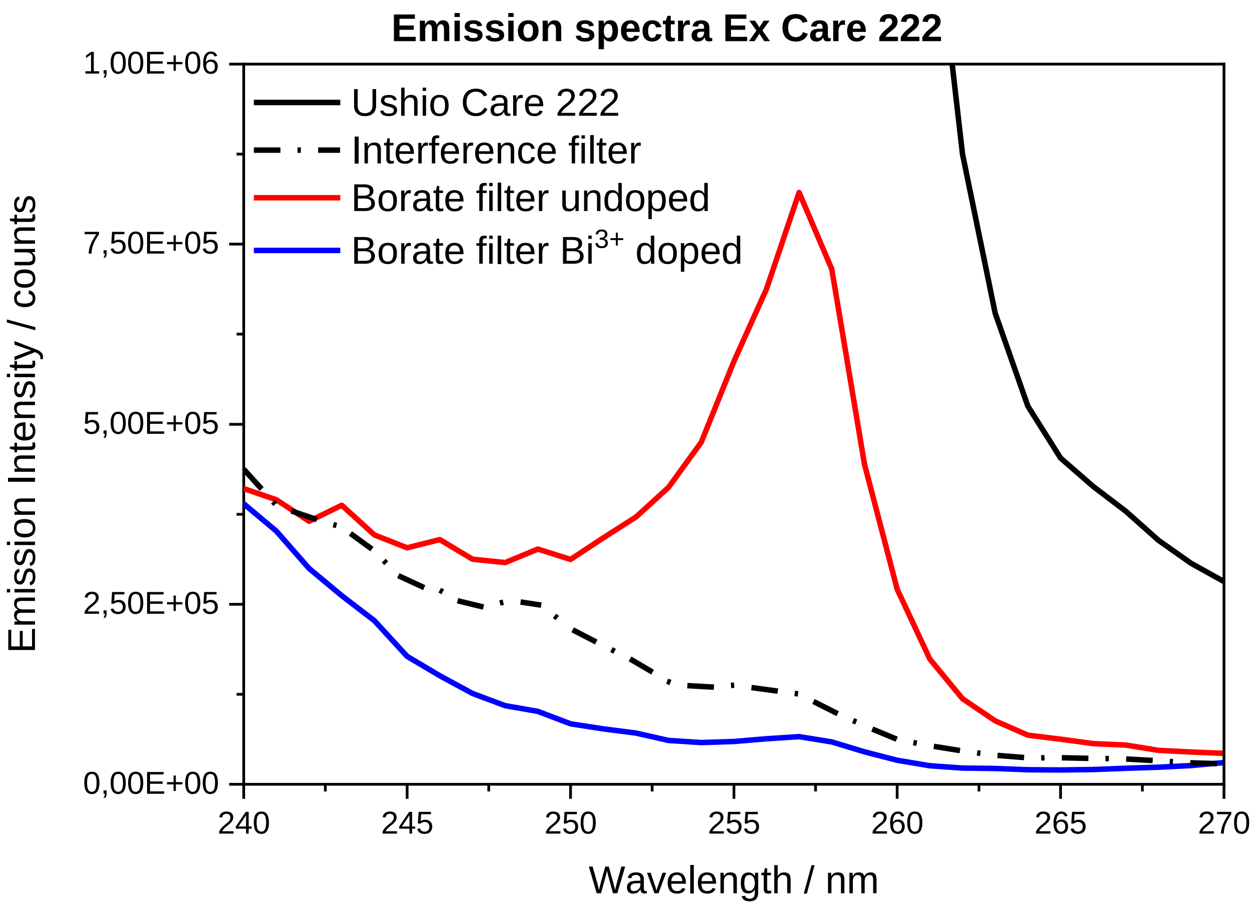
Application of $(Y,Lu)BO_3$ Doped with Bi^{3+}

Coated quartz slides were used for spectroscopic characterisation

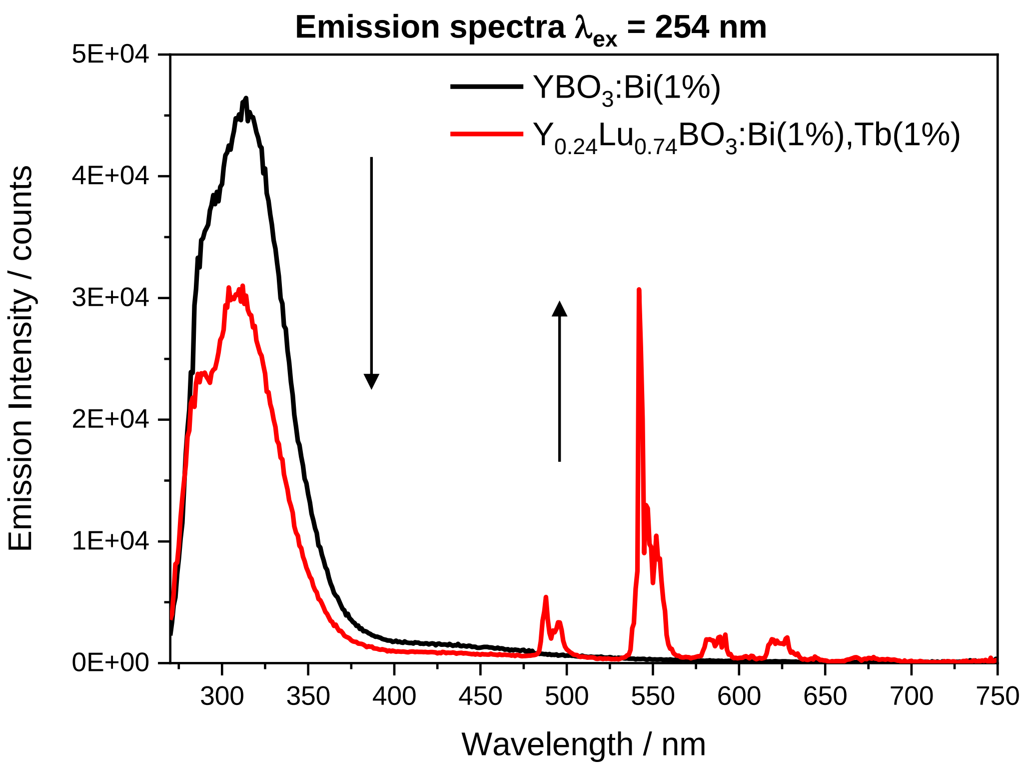


Results

- **The Bi^{3+} doped $(Y,Lu)BO_3$ filter shows the strongest reduction of the undesired emission between 240 and 270 nm**
- **Strong scattering also reduces the overall 222 nm intensity**

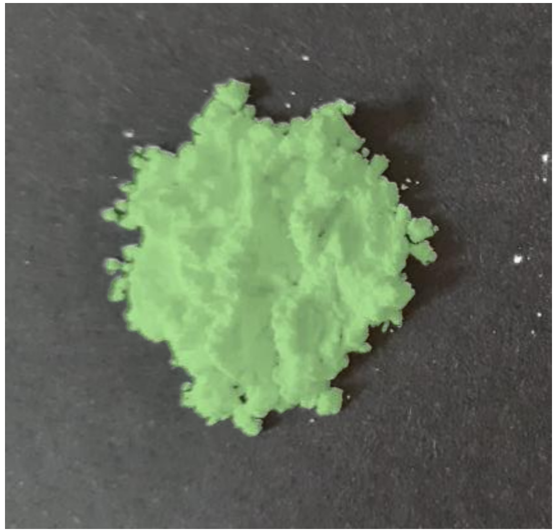
6. UV-C Filter Materials

Energy Transfer to Shift Harmful Bi^{3+} UV-B Emission to Lower Energy (VIS or NIR)



The $Bi^{3+} \rightarrow Tb^{3+}$ energy transfer reduces the UV-B emission of Bi^{3+} and yields green Tb^{3+} emission

$Y_{0.24}Lu_{0.74}BO_3:Bi^{3+}$ under 254 nm excitation



$Y_{0.24}Lu_{0.74}BO_3:Bi^{3+},Tb^{3+}$ under 254 nm excitation

Other ET schemes

$Bi^{3+} \rightarrow Eu^{3+}$ red emission, ET efficient but CT band of Eu^{3+} in the UV-C

$Bi^{3+} \rightarrow Nd^{3+}$ NIR emission, but ET not efficient

$Bi^{3+} \rightarrow Ho^{3+}$ NIR emission, ET efficient

7. Summary

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Deep UV-C Emitting Radiation Sources

• LEDs or laser diodes		230 - 240 nm	lifetime?
• 450 nm LEDs or laser diodes + deep UV-C up-converter		225 nm	efficiency?
• Excimer discharge lamp	KrBr*	207 nm	side bands
	KrCl*	222 nm	side bands
• Xe_2* Excimer discharge lamp + deep UV-C phosphor		200 - 240 nm	side bands
• x-ray tube + deep UV-C phosphor		200 - 240 nm	
• Cathode-ray tube + deep UV-C phosphor		200 - 240 nm	

7. Summary

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Deep UV-C Emitting Conversion Materials / Filter for KrCl* discharge lamps

Conversion materials

- Suitable activator ions are Pr^{3+}, Bi^{3+}, and Sc^{3+}, however, broad band emission is not limited to 200 – 240 nm, thus a filter is required yet
- Phosphor must be long-term stable upon VUV, x-ray, or electron excitation

Filter for KrCl* excimer discharge lamps

- Wide band gap and radiation hard host material required
- Absorption at the low energy edge cannot be achieved by the band edge → dopant is required
- Most suitable dopant is Bi^{3+} in borates, which emits in the UV-B/A range
- UV-B/A emission can be suppressed by energy transfer due to a co-dopant, e.g. Tb^{3+} or other NIR emitting RE ions

Application areas

• TOC removal (herbizides, hormones, pharmaceuticals, PFAS)	< 250 nm
• Indoor air disinfection	200 – 240 nm
• Nitrate decomposition	< 240 nm
• Photocatalytical synthesis at RT	200 – 240 nm

8. References

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Internet Links

- Homepage T. Jüstel — www.fh-muenster.de/juestel
- Ushio — www.ushio.com
- Signify — www.signify.com

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