Glass in energy

Glasses for solar energy I: low-E and solar control glass

MAT 498

Lehigh University

The use of glass in solar energy involves two general types of applications:

- bulk glass applications, requiring specific optical, thermal and chemical glass properties, such as glass tubing in solar thermal concentrators (in concentrated solar power, CSP);

- applications where glass is essentially a substrate for functional coatings (generally not glassy), which include again CSP (glass mirror substrates), but also low emissivity and solar control glass windows, solar panel glass windows, photovoltaic (PV) panels and photocatalytic (photochemical) self-cleaning glasses.

The scale of solar systems ranges from power plants to individual power units.

The four main applications which will be considered are, therefore:

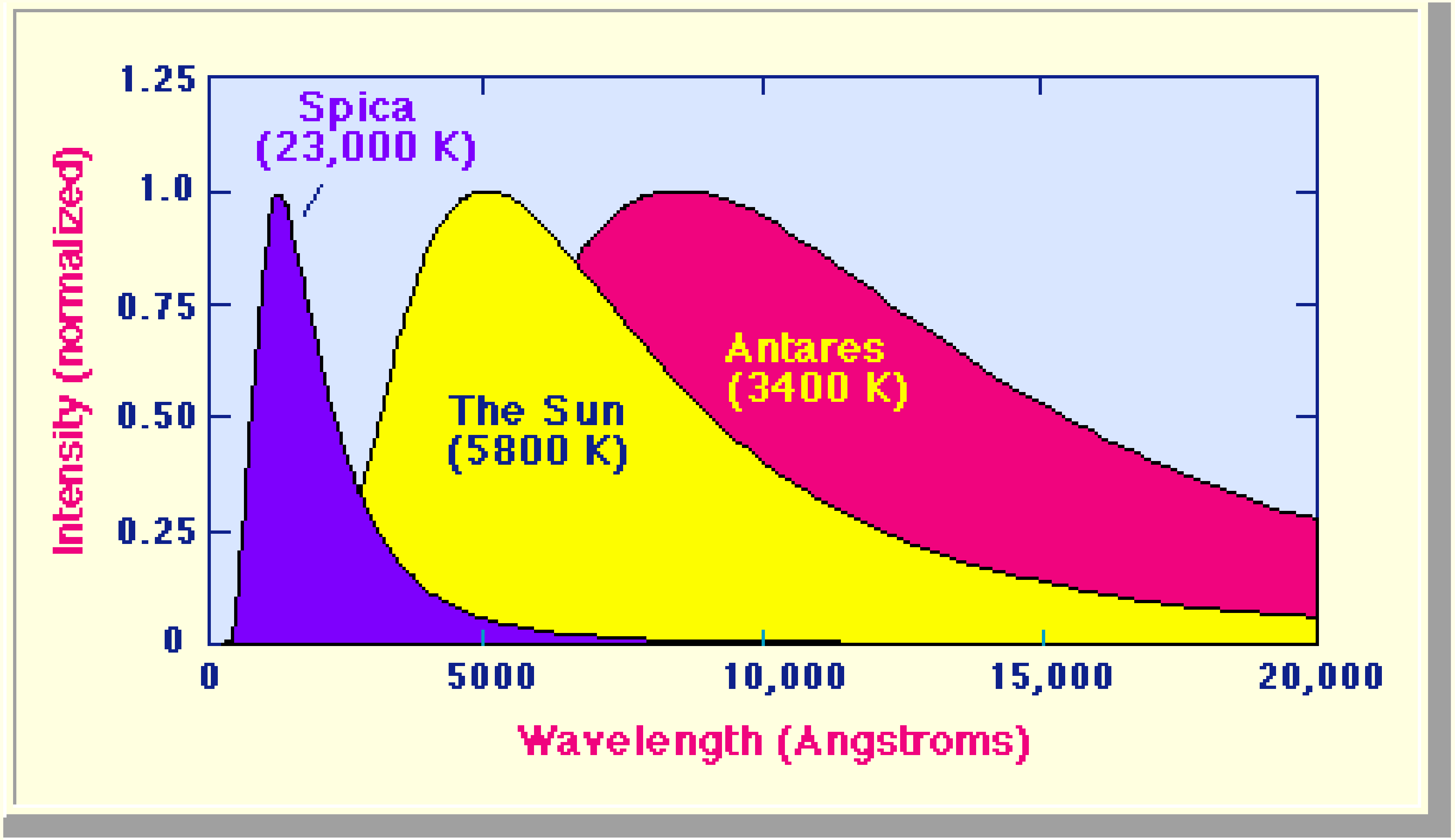
→ - solar control glass (namely low emissivity) - today's **lecture 4**

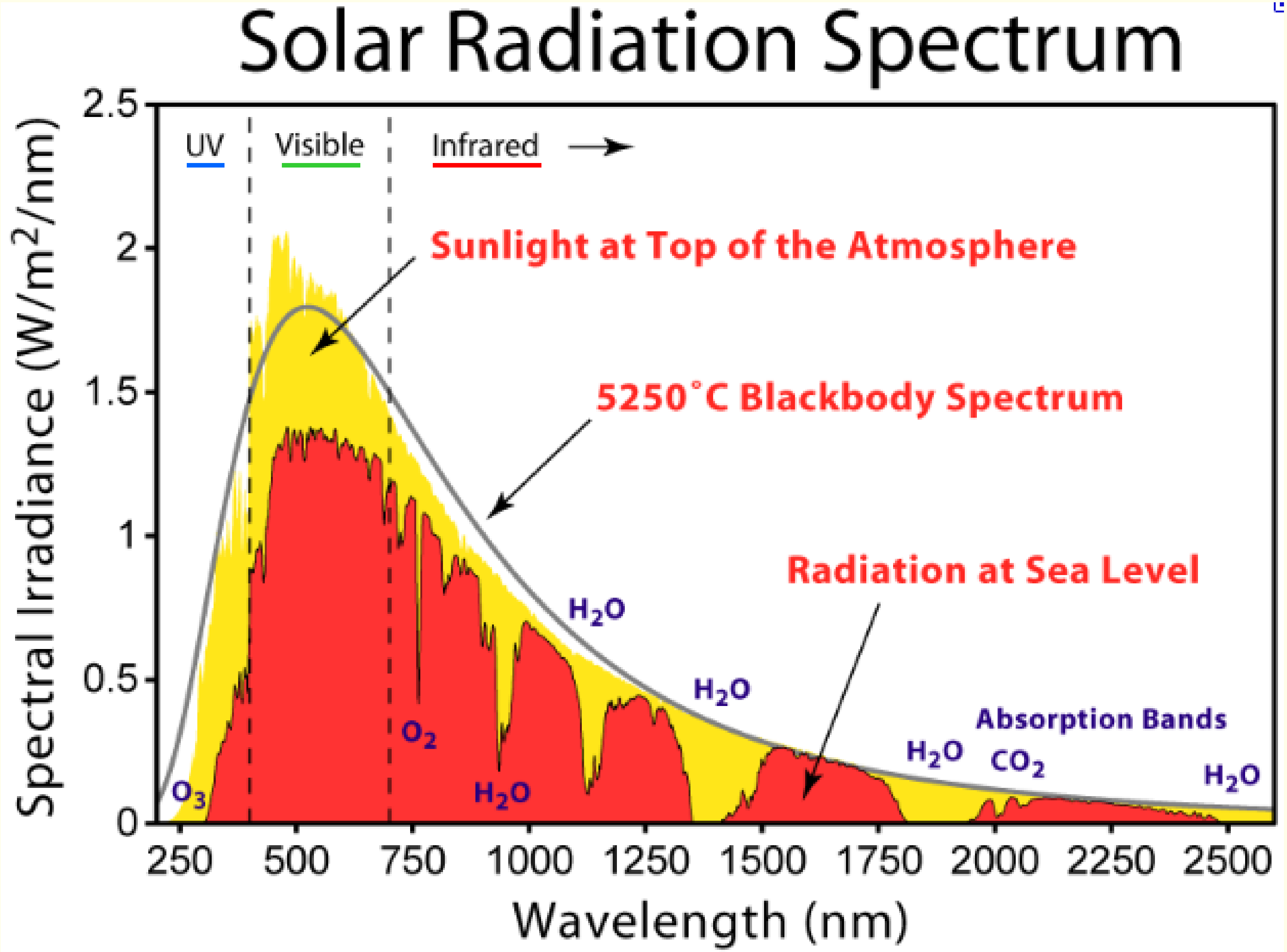
- thermal: including solar concentration (parabolic trough and flat heliostat mirror technologies) and solar hot water panels; - lecture 5

- photovoltaic (glass containing) panels, including solar panel glass windows; - lecture 6

- photochemical (namely photocatalytic, self-cleaning glass windows) "

The solar spectrum





Adapted from: http://www.google.co.uk/imgres?q=solar+radiation+spectrum&hl=pt- (20 Jan 2012)

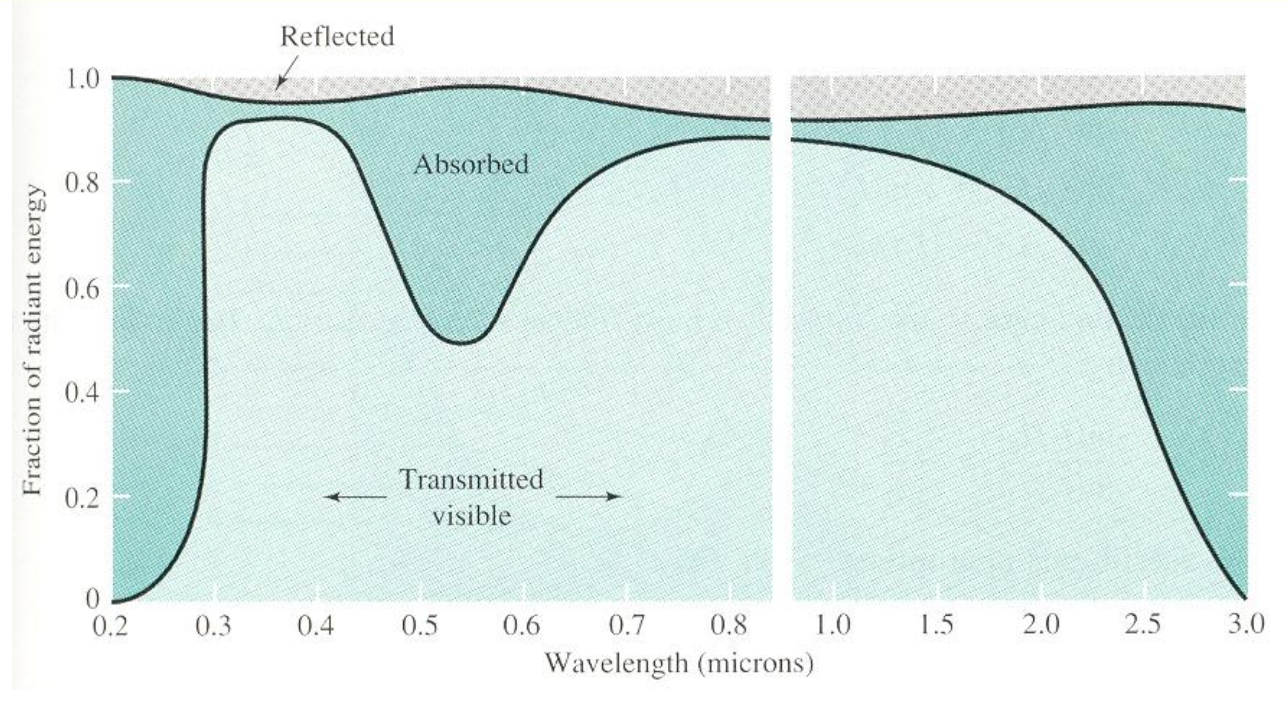
From the second lecture, Kirchoff's law; its more general form is:

$$T + A + R + S + K = 1$$

(Transmitted + Absorbed + Reflected + Scattered + emitted = 100 %)

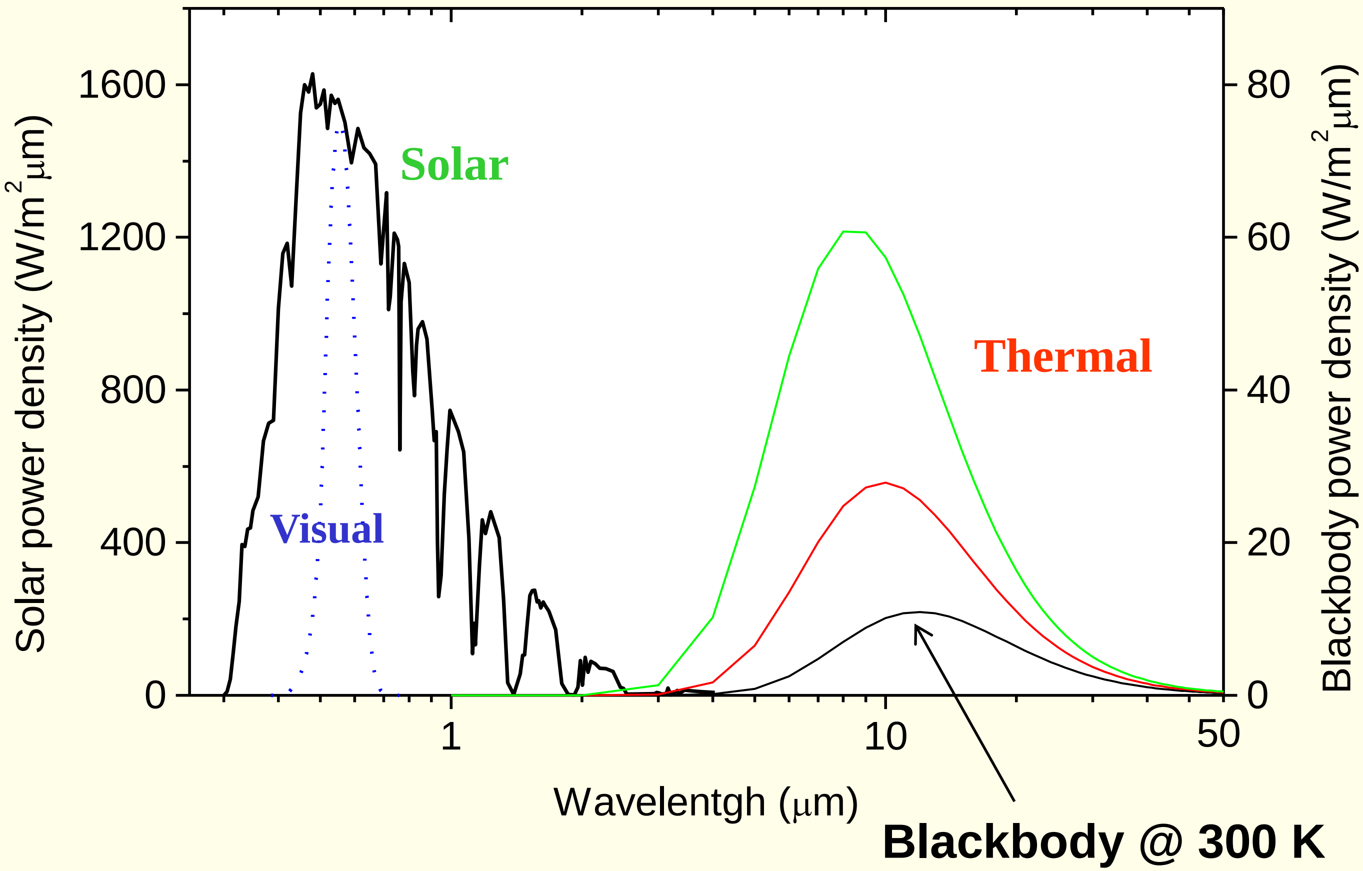
Sun light can be: transmitted, absorbed, reflected, scattered and re-emitted by a glass window. Scattering by architectural glass is negligible.

The emissivity of a glass is the ability of a glass surface to radiate energy when its temperature rises above that of its surroundings.

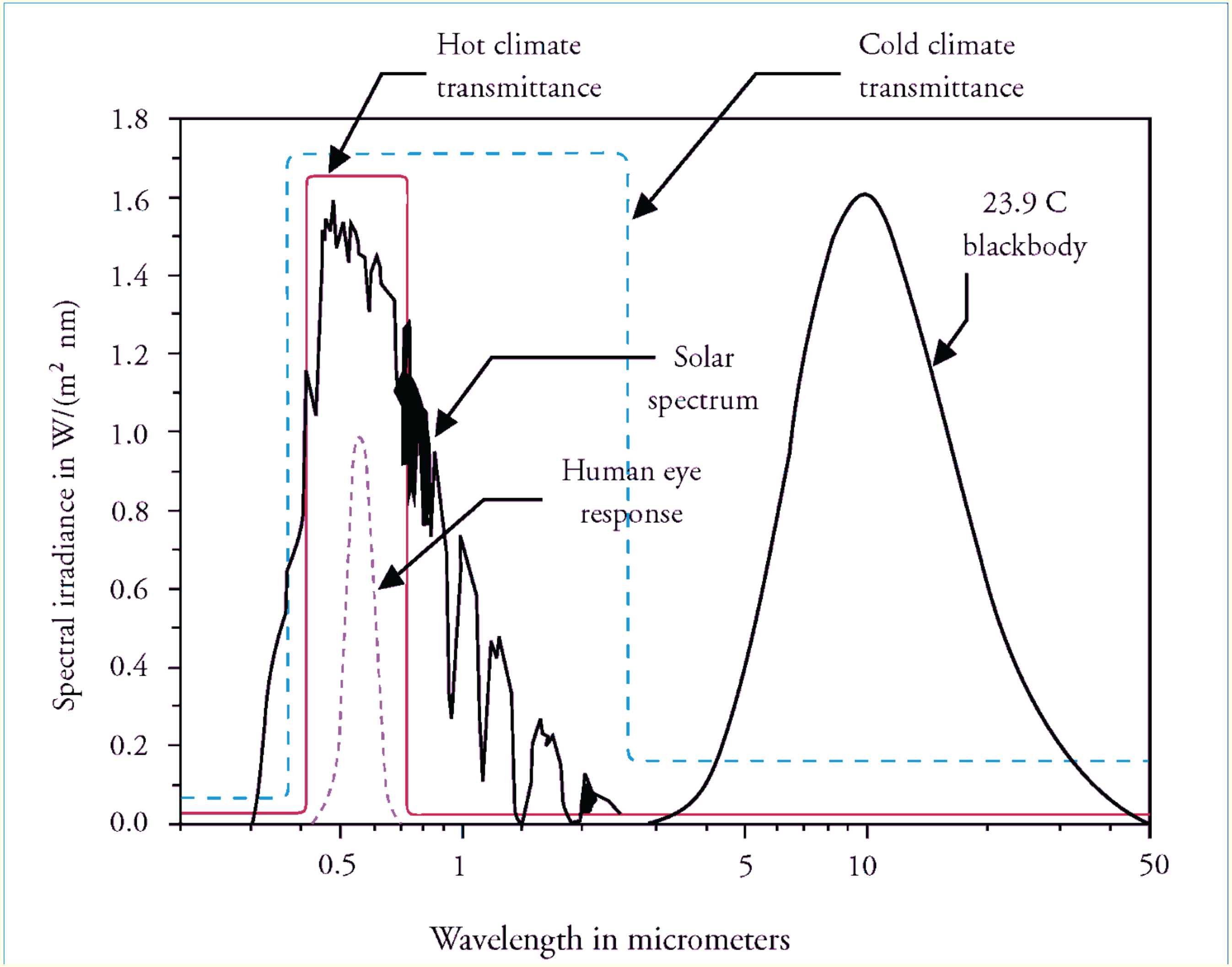


(Adapted from: *The science and design of engineering materials*, McGraw-Hill, 1999)

Solar and thermal spectral distributions



- Solar and thermal spectral distributions, and two idealized window transmission spectra



Glass for a sustainable society

Window coatings for **energy efficiency**

Active coatings

"smart"

Thermochromic
Photochromic
Electrochromic

Passive coatings

"non-switchable"

Anti-reflection
Up/down converting
Low-E
Solar control

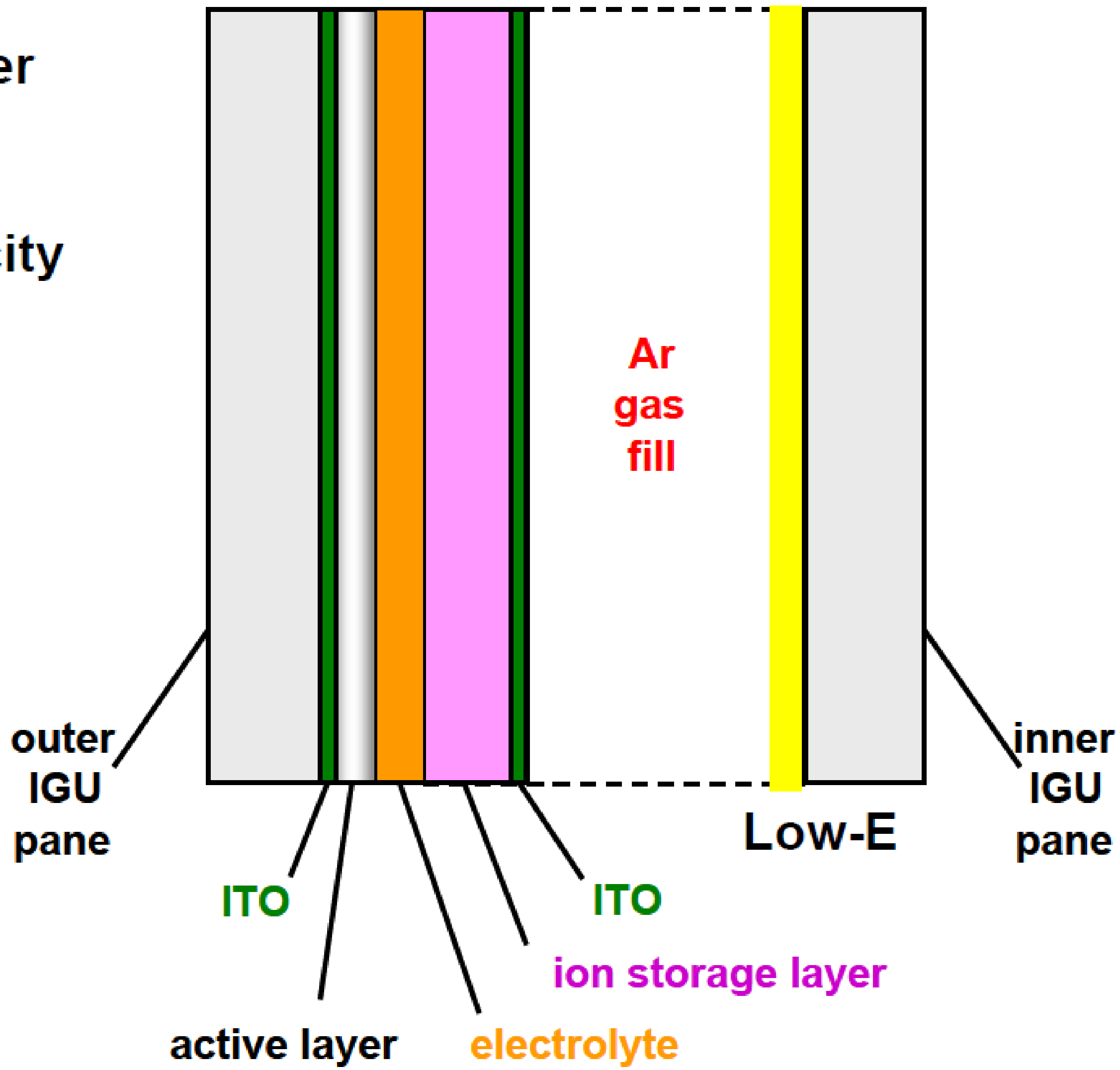
Conventional Electrochromic Windows

- transmission 50% - 13%
- Blue in transmission (WO_3-based)
- Minimal reflectance control
- Complex multilayer design
- Still expensive

Adapted from: Windows of the Future, Andre Anders (Lawrence Berkeley Laboratory), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Conventional Electrochromic Windows

- ✓ Metal oxide active layer and ion storage layer
- ✓ Limited storage capacity
- ✓ Many coatings, thick layers



Adapted from: Windows of the Future, Andre Anders (Lawrence Berkeley Laboratory), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Flat (window) glass is currently coated with passive coatings in order to reduce heat transfer.

To improve the energy efficiency of windows, more and more commercial architectural glass is being coated with films which allow solar radiation to pass through, but reduce heat transfer (particularly the emissivity).

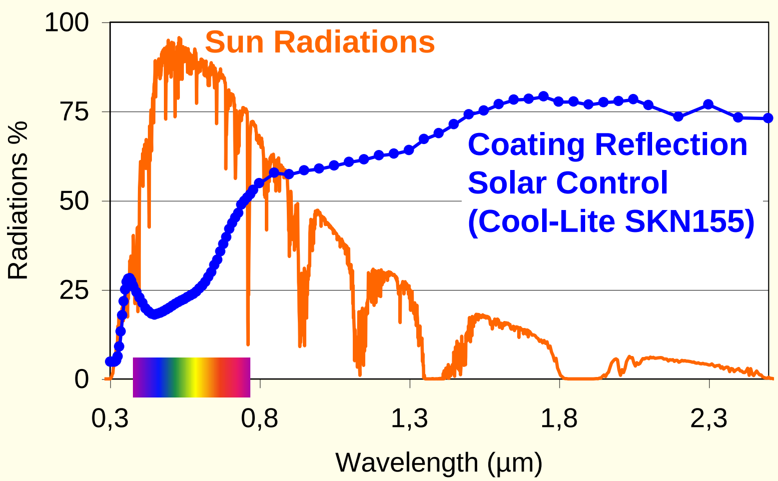
Coating processes include spray pyrolysis, CVD, sputtering and microwave heating; the latter two can be applied online. With microwave heating, only the glass is heated and not the furnace atmosphere. Sol-gel is also a possible alternative.

- **Low emissivity glass**

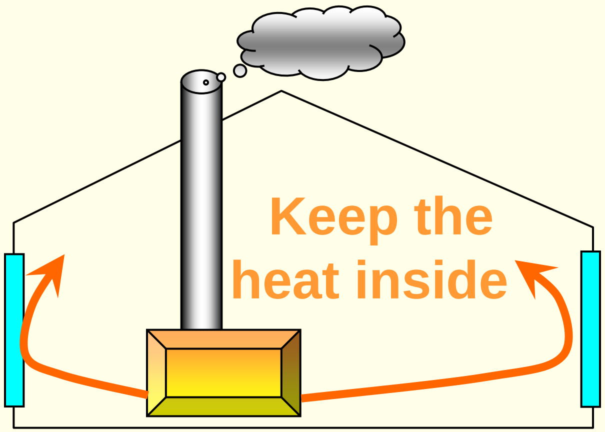
- **Solar control glass**

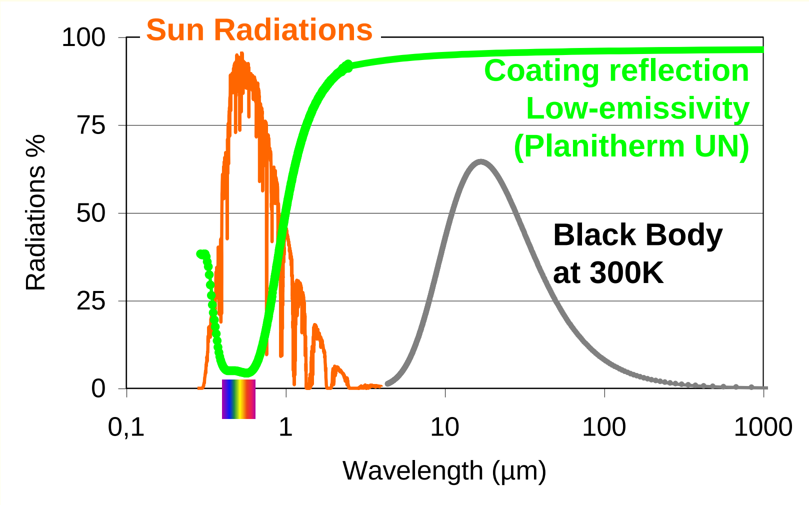
Two functions to reduce heat transfer

- Solar Control



- Low Emissivity





From: Chuck Anderson, Saint-Gobain Recherche, Montpellier EFONGA Workshop, 2009

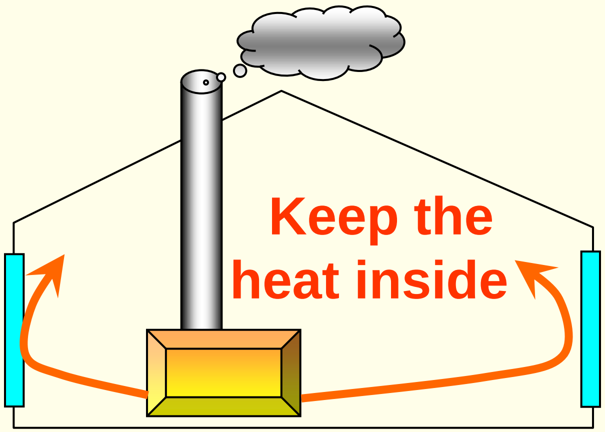
Low-emissivity glass coatings for energy savings in buildings

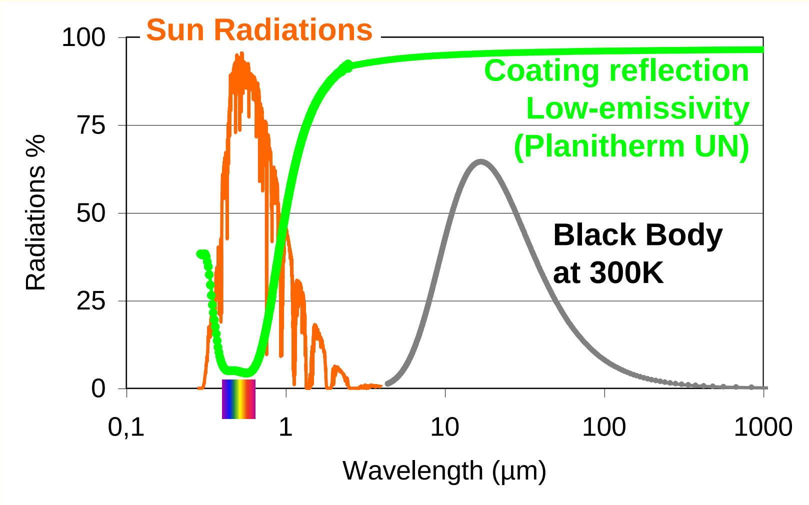
Substantial energy savings in buildings can be achieved by the use of **double-glazed** insulating glass **windows** (or IGU – insulating glass units) which reduce heat transfer through the air/gas sandwiched layer and particularly by double glass pane windows coated on the inside with a low emissivity (low-E) coating.

Such coating is usually deposited by spray pyrolysis (hard pyrolitic metal oxide coating), by CVD or by sputtering (soft multilayer coating formed by different types of alternating metal and metal oxide layers). Often, such coatings are made of F-doped tin oxide (**SnO_2:F**), but they may also be made of other oxides like ZnO, **In_2O_3** or TiO_2, whereas the metal layers may consist of **Ag**, Al, Ti, Zn, Sn, Ni, Cr, or stainless steel.

• Low Emissivity

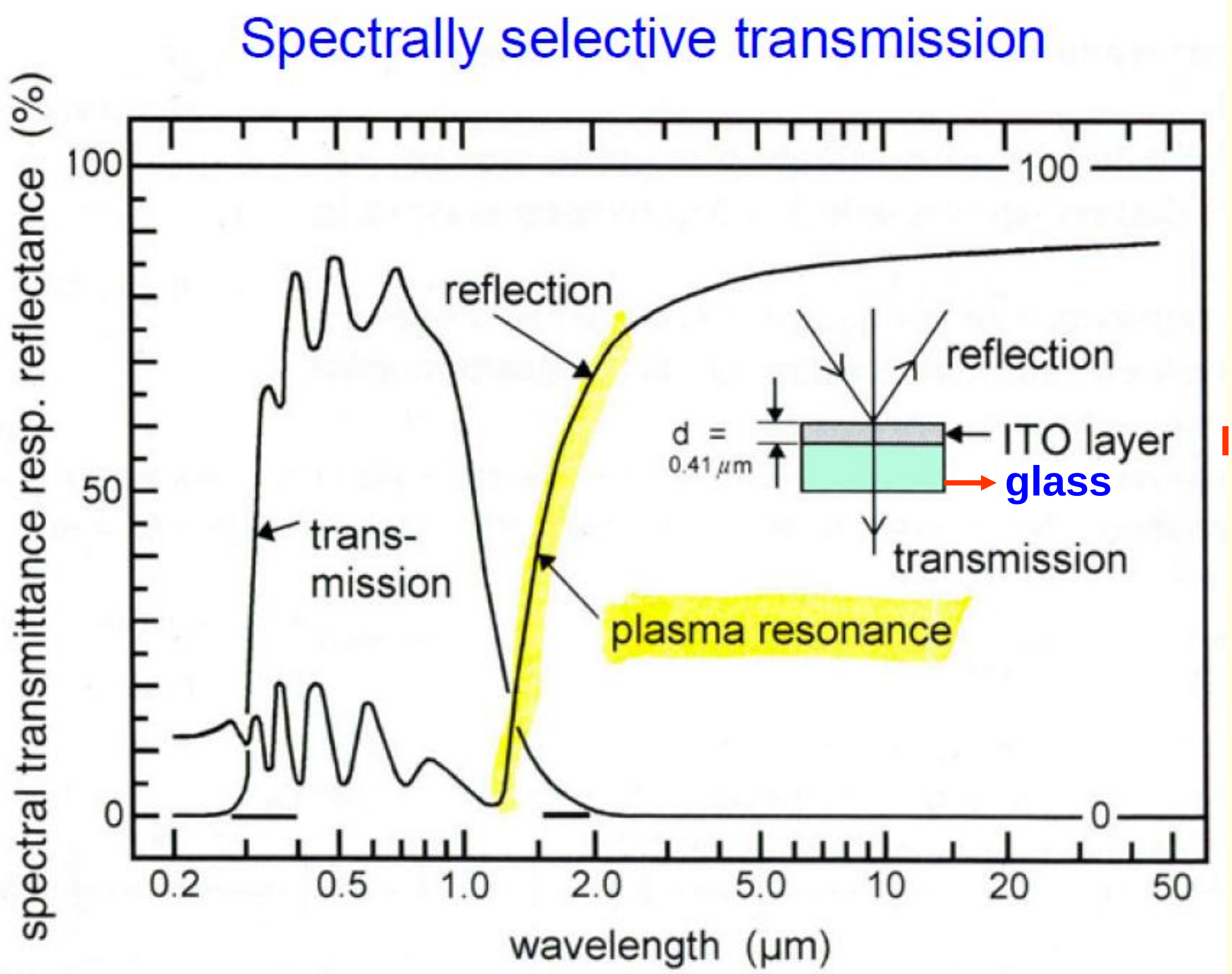
A low-E coating transmits short-wave visible light into the building (while absorbing UV and short-wave IR), but reflects long-wave thermal radiation back inside the building (inside pane of glass).





Adapted from: Chuck Anderson, Saint-Gobain Recherche, Montpellier EFONGA Workshop, 2009

Low Emissivity (Low-E)

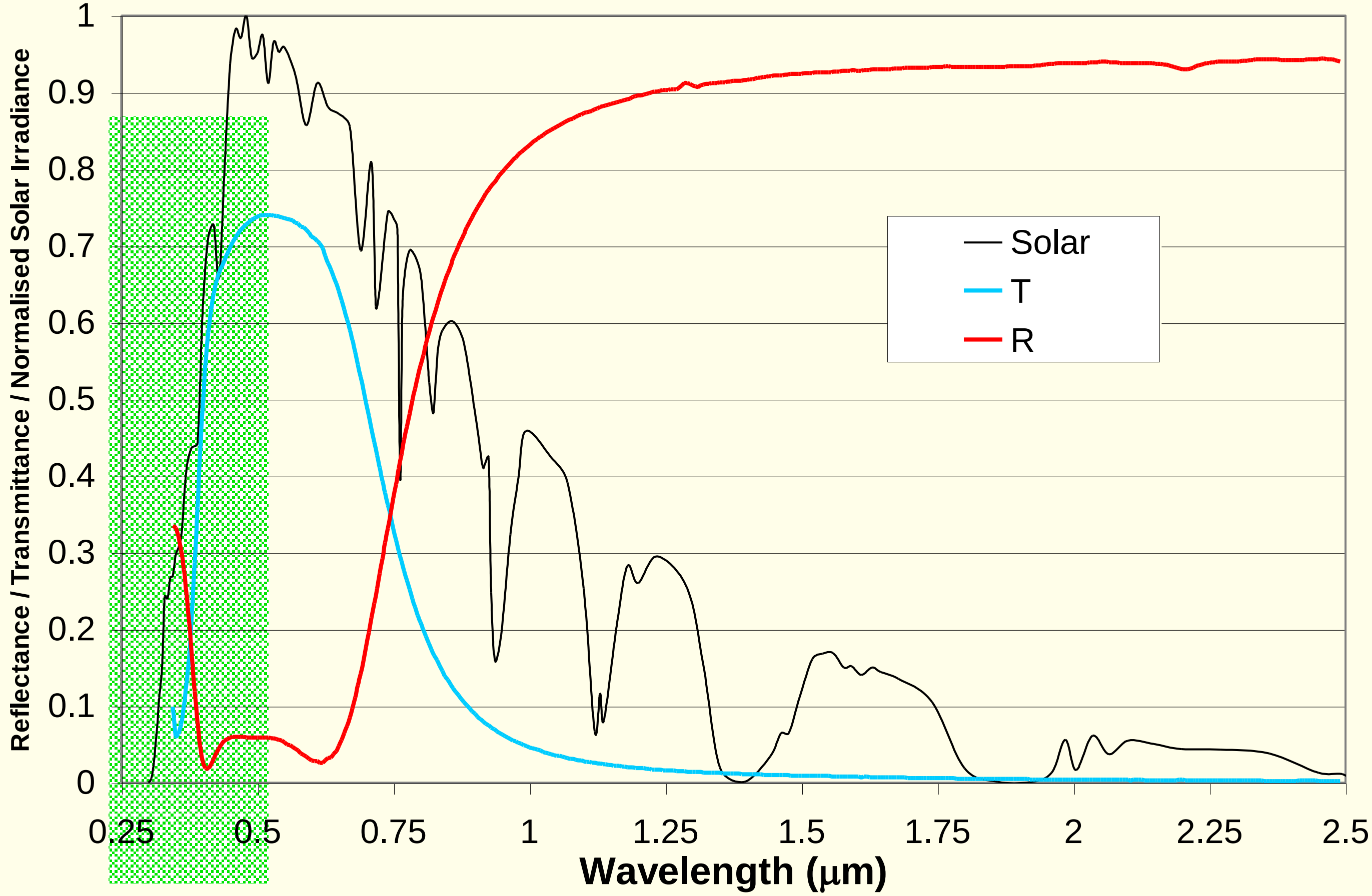


In_2O_3:Sn

Adapted from: Windows of the Future, Andre Anders (Lawrence Berkeley Laboratory), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

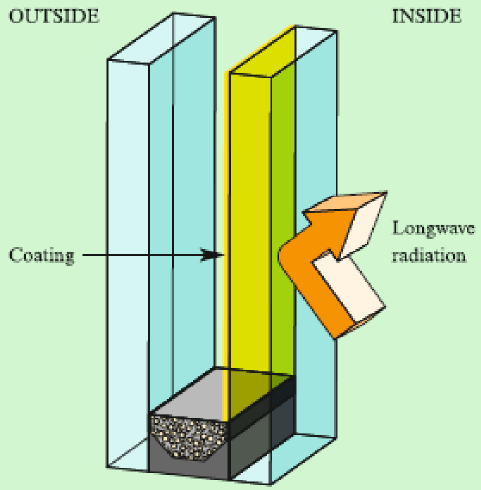
Sun ~ 0.3 – 3.0 µm

Optical properties of Ag-based low-E coated glass



From: Chuck Anderson, Saint-Gobain Recherche, Montpellier EFONGA Workshop, 2009

IGU



keeps the heat inside

Insulating Glass Unit incorporating low-e glass

Low-E glass

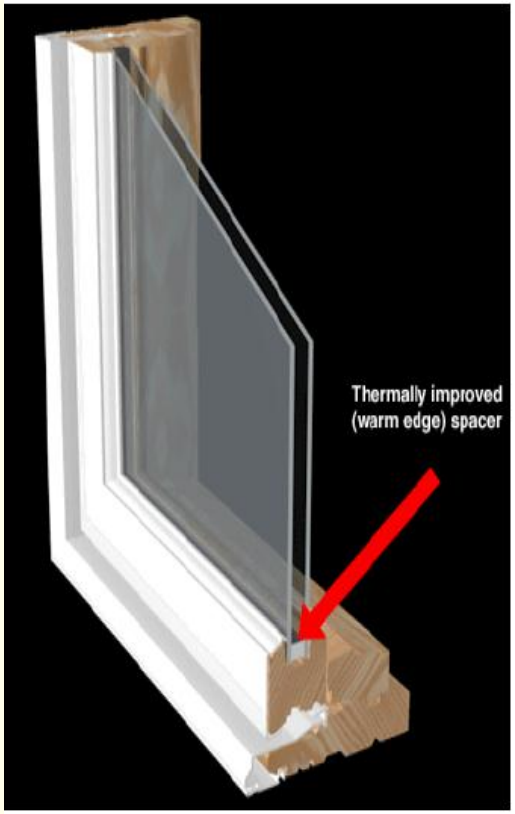
Solar energy enters the building mainly as short wave radiation but, once inside, it is reflected back by objects towards the glass as long wave radiation. Low-emissivity glass has a coating that allows the transmission of the sun's short wave radiation at a much higher rate than long wave radiation (from the heaters and objects in the room), providing an effective barrier to heat loss. To maximise energy efficiency all year round, often the ideal glazing solution balances both solar control and low-emissivity performance.

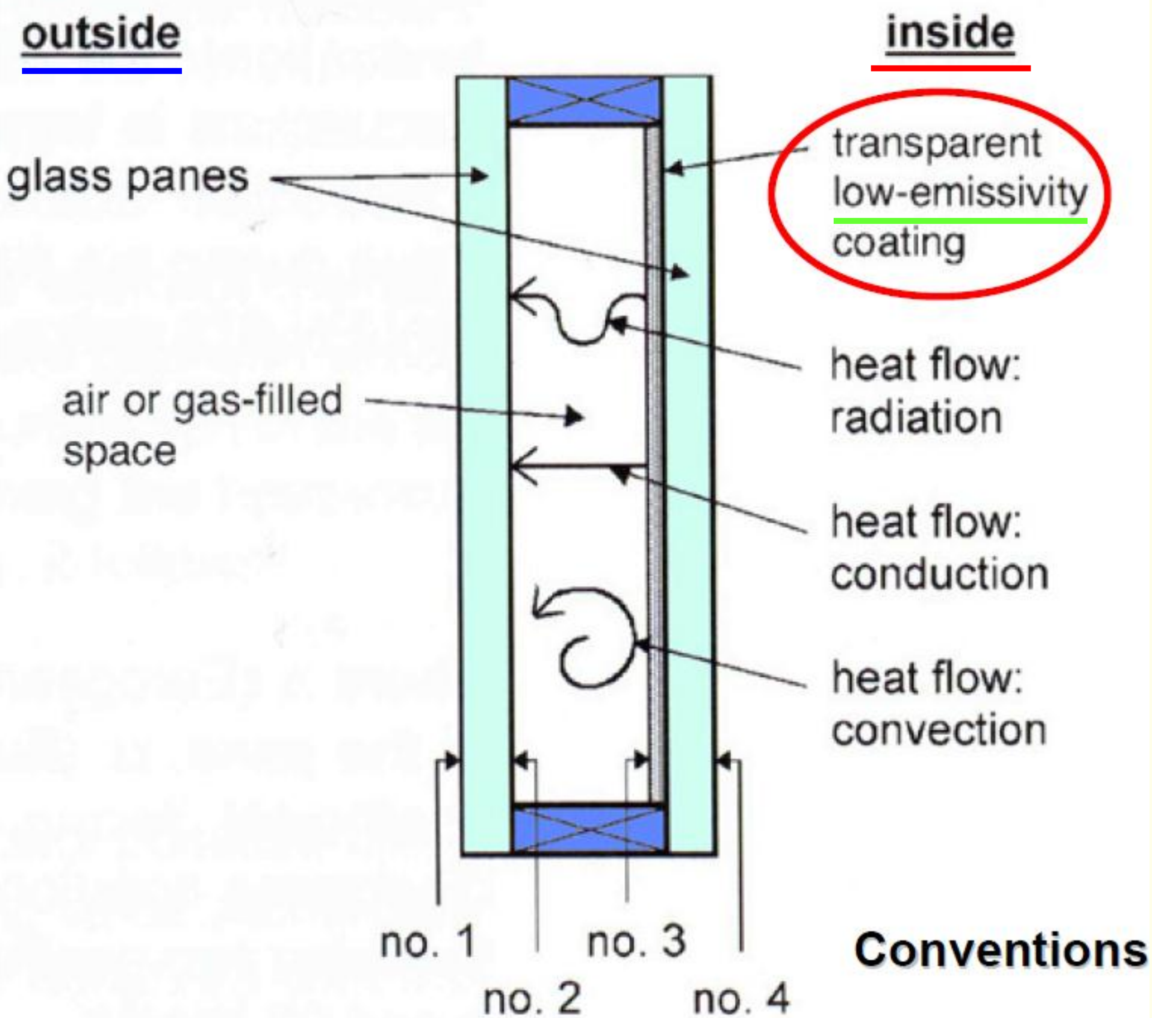
Low-E coatings are usually metal or metal oxides which reduce the amount of heat which enters or escapes the home through the windows. They also block UV rays, reducing fading to furniture, etc. .

In cold climates, to keep the heat inside, the coating should be applied to the interior pane of the glass (as shown).

In warmer climates, to keep heat from entering the home, the coating should be applied to the exterior pane (like in solar control glass).

Insulated Glass Unit - IGU
incorporating low-E glass coating





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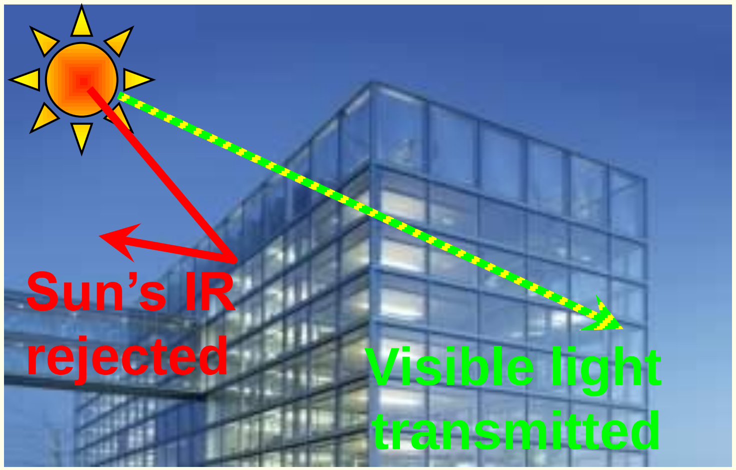
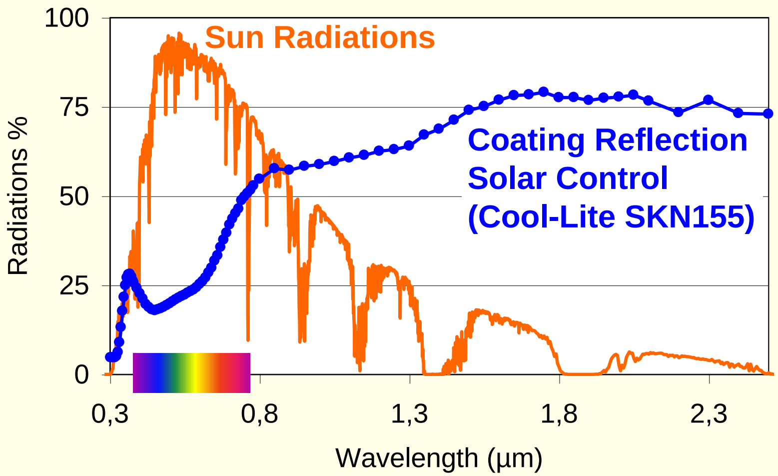
Adapted from: Windows of the Future, Andre Anders (Lawrence Berkeley Laboratory), International Workshop on Glass for Harvesting, Storage and Efficient Usage of Solar Energy, Nov. 16-18, 2008, Pittsburgh, PA

Solar control

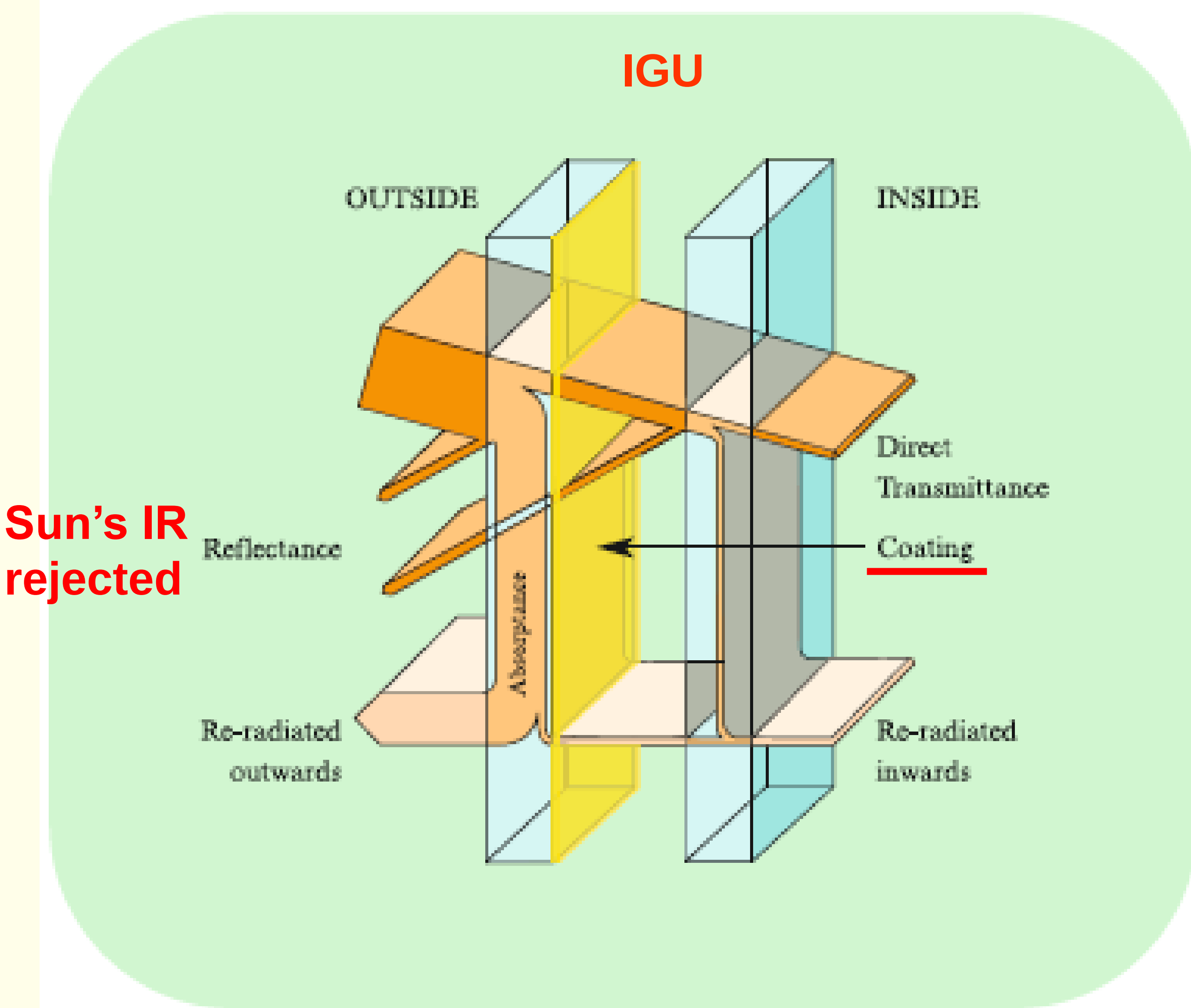
- Solar Control





A **solar control** coating reflects near-UV and near-IR radiation from the sun, while transmitting the visible portion.

Adapted from: Chuck Anderson, Saint-Gobain Recherche, Montpellier EFONGA Workshop, 2009



Insulating Glass Unit incorporating coated solar control glass

While low emissivity often relies on coatings prepared by deposition in vacuum (namely by magnetron sputtering)**, sol-gel is a less expensive alternative technique to prepare solar control glass coatings for energy efficient windows in architectural, automotive and microwave applications.**

This method enables the preparation of multilayer coatings which have selective high reflectivity properties in the NUV and NIR domains.

Objectives

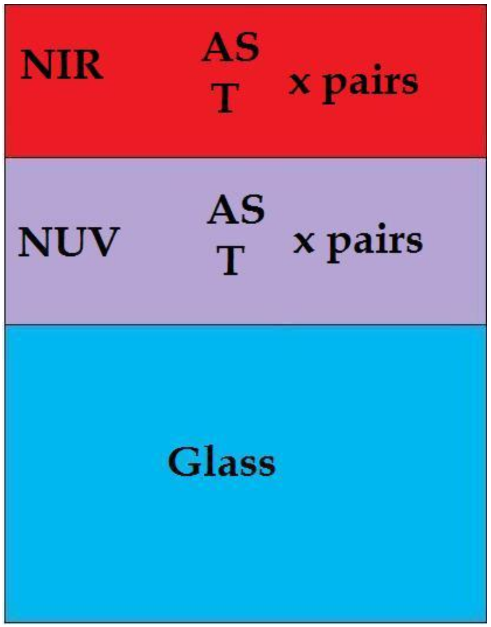
- To develop sol-gel glass coatings for solar control: only ~ half of the solar energy (the visible part) is transmitted, while the near-UV (NUV) and NIR are reflected as much as possible.

- Using Bragg mirrors (BMs), photonic bandgap-type coatings with high reflectivity in: NUV and NIR.

- These Bragg mirrors are multi-layered alternating silicate glass/titania coatings, prepared by sol-gel, with a single layer thickness $x = \lambda_c / 4n$, λ_c being the peak wavelength of the *stop band* of high reflectivity and n its refractive index.

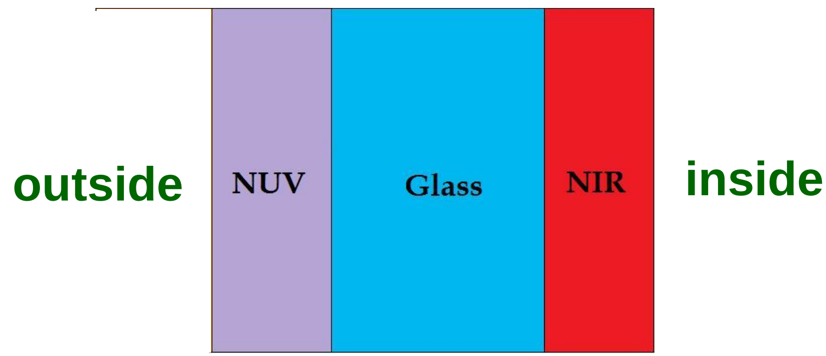
- Aim: to cover a glass window with two different BMs: (1) a NUV-reflecting BM and (2) a NIR-reflecting BM. In real life, the films will be prepared by sol-gel and deposited by roller- or spray-coating, e.g..

•Using Bragg mirrors (BMs), which are 1-D photonic bandgap-type coatings with high reflectivity in: near-UV and near-IR.



AS – Aluminosilicate

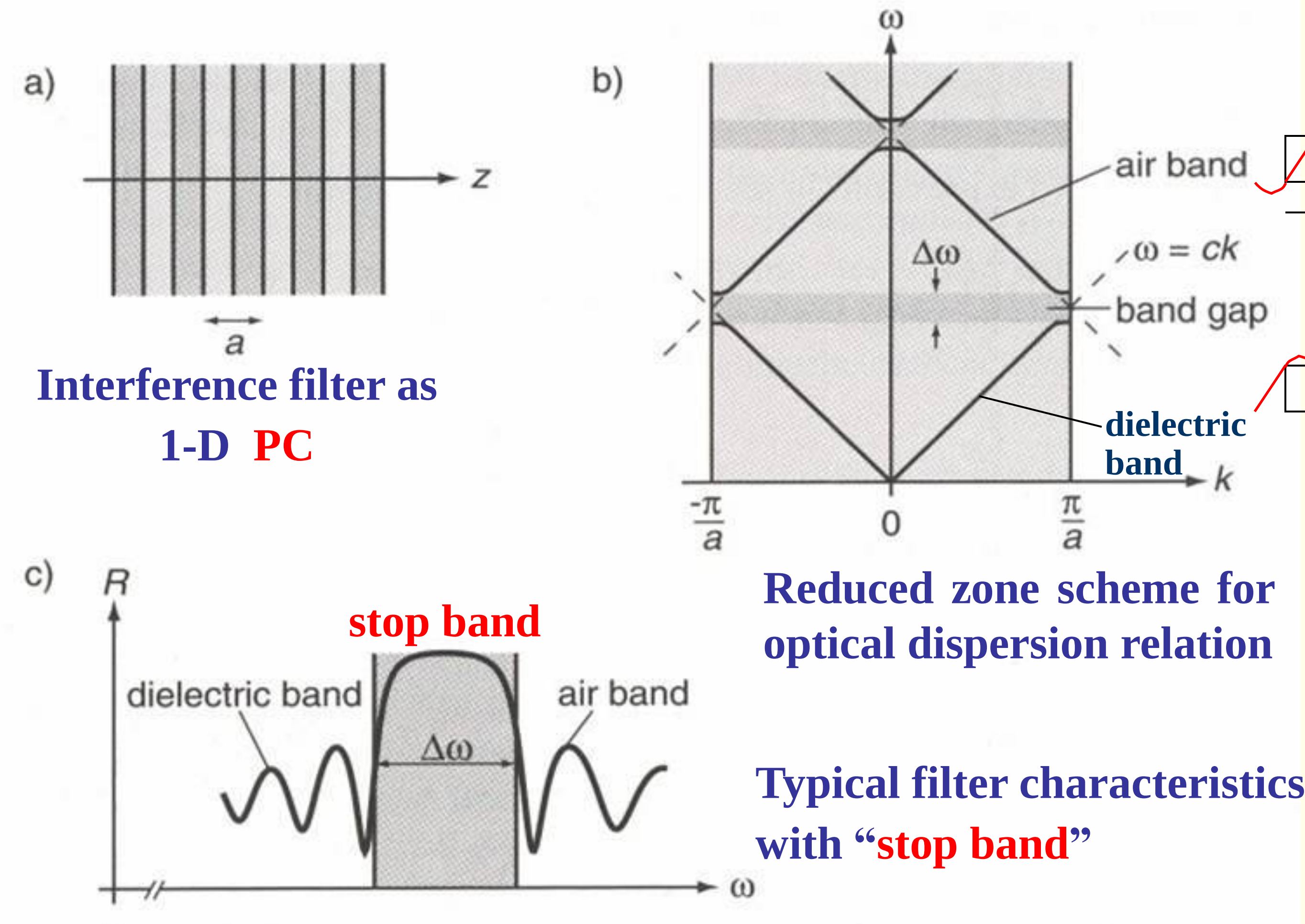
T - Titania



Prototype (single pane)

Interference filter

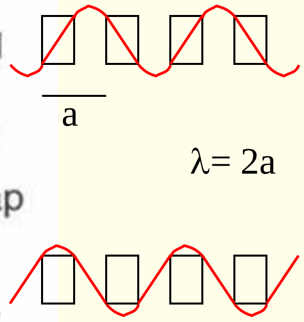
(Distributed Bragg Reflector, DBR, or simply a **Bragg Mirror, BM)**



Interference filter as 1-D PC

Reduced zone scheme for optical dispersion relation

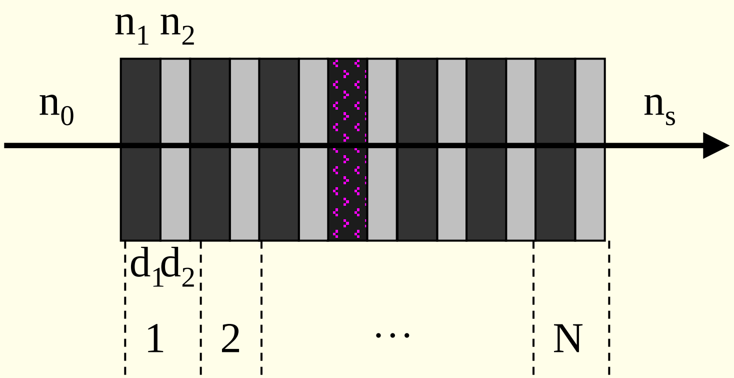
Typical filter characteristics with "stop band"



$$\omega_a = \frac{c_0}{n_a} k$$

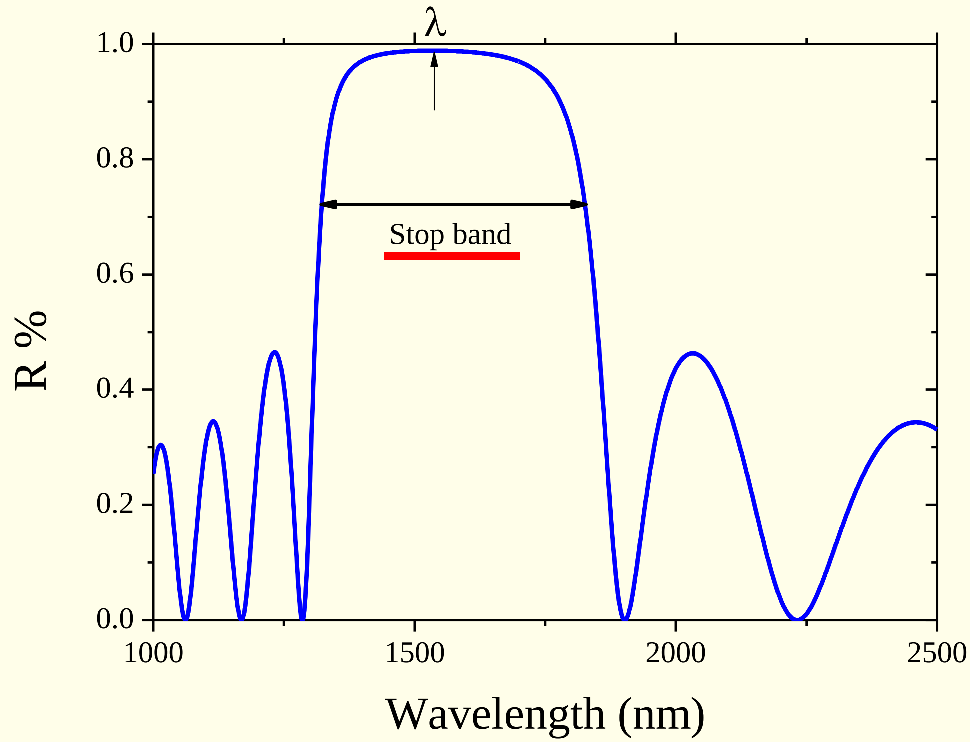
$$\omega_d = \frac{c_0}{n_d} k$$

Distributed Bragg Reflector (Bragg mirror)



$$n_1 d_1 = n_2 d_2 = \lambda / 4$$

$$R = \left(\frac{n_0 (n_2)^{2N} - n_s (n_1)^{2N}}{n_0 (n_2)^{2N} + n_s (n_1)^{2N}} \right)^2$$



- The higher the refractive index contrast and the more DBR periods, the higher the reflectivity.
- The individual (high and low index) layers are transparent.

Simulations of BM spectral responses

(Transfer Matrix Method)

Transfer matrix method (TMM)

The reflection spectrum of a BM structure, φ_{cav}, can be calculated by the **transfer matrix method** (TMM). In the present case, only light at normal incidence was considered:

$$\varphi_{cav} = \frac{n_{Si}}{S_{11}S_{11}^{*}}$$

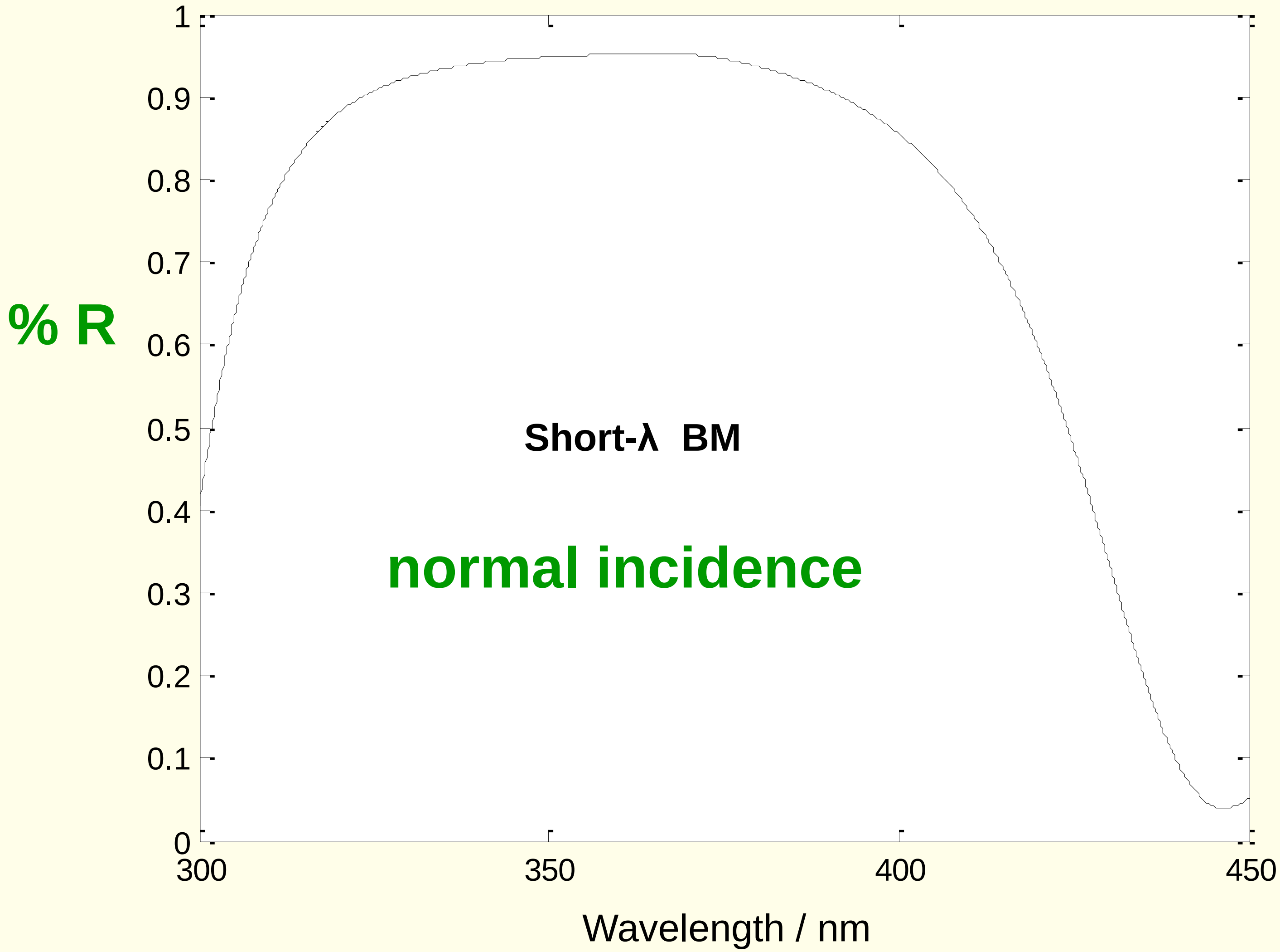
where n_{Si} is the refractive index of the (Si) substrate and S_{11} is the (1, 1) element of the transfer matrix S, defined as:

$$S = \begin{pmatrix} 1 & 1 \\ n_o & -n_o \end{pmatrix}^{-1} \times \prod_{k=1}^{N} \begin{pmatrix} \cos\frac{2\pi}{\lambda} n_k d_k & \frac{i}{n_k}\sin\frac{2\pi}{\lambda} n_k d_k \\ i n_k \sin\frac{2\pi}{\lambda} n_k d_k & \cos\frac{2\pi}{\lambda} n_k d_k \end{pmatrix} \times \begin{pmatrix} 1 & 1 \\ n_{Si} & -n_{Si} \end{pmatrix}$$

here $n_o = 1$ is the refractive index of air, N is the total number of alternating layers, λ is the wavelength of light and n_k and d_k are the refractive index and thickness of each layer.

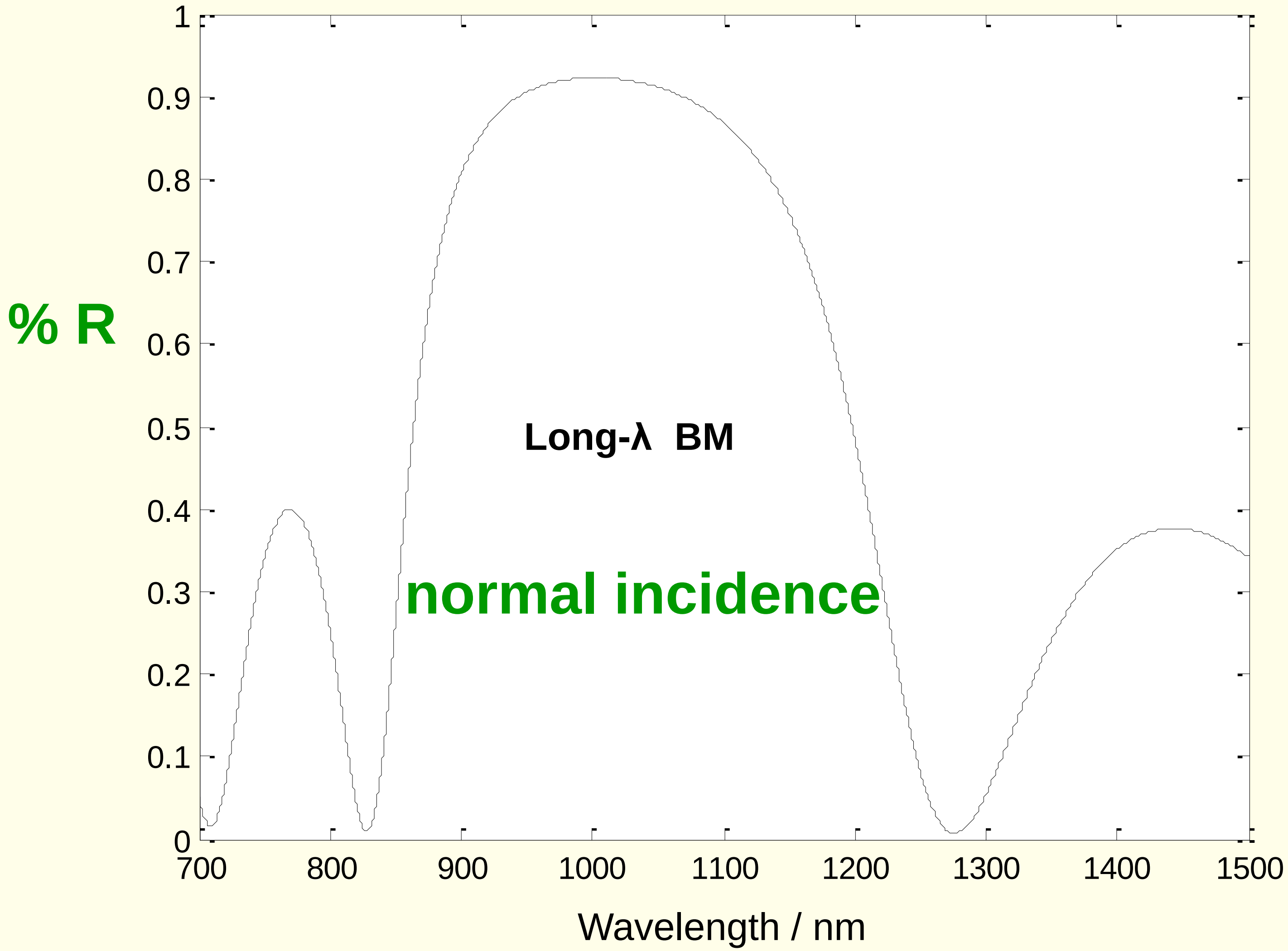
Si / $(TS)_4$ TMM simulation n_S = 1.44 n_T = 2.0

x_S = 60 nm x_T = 45 nm

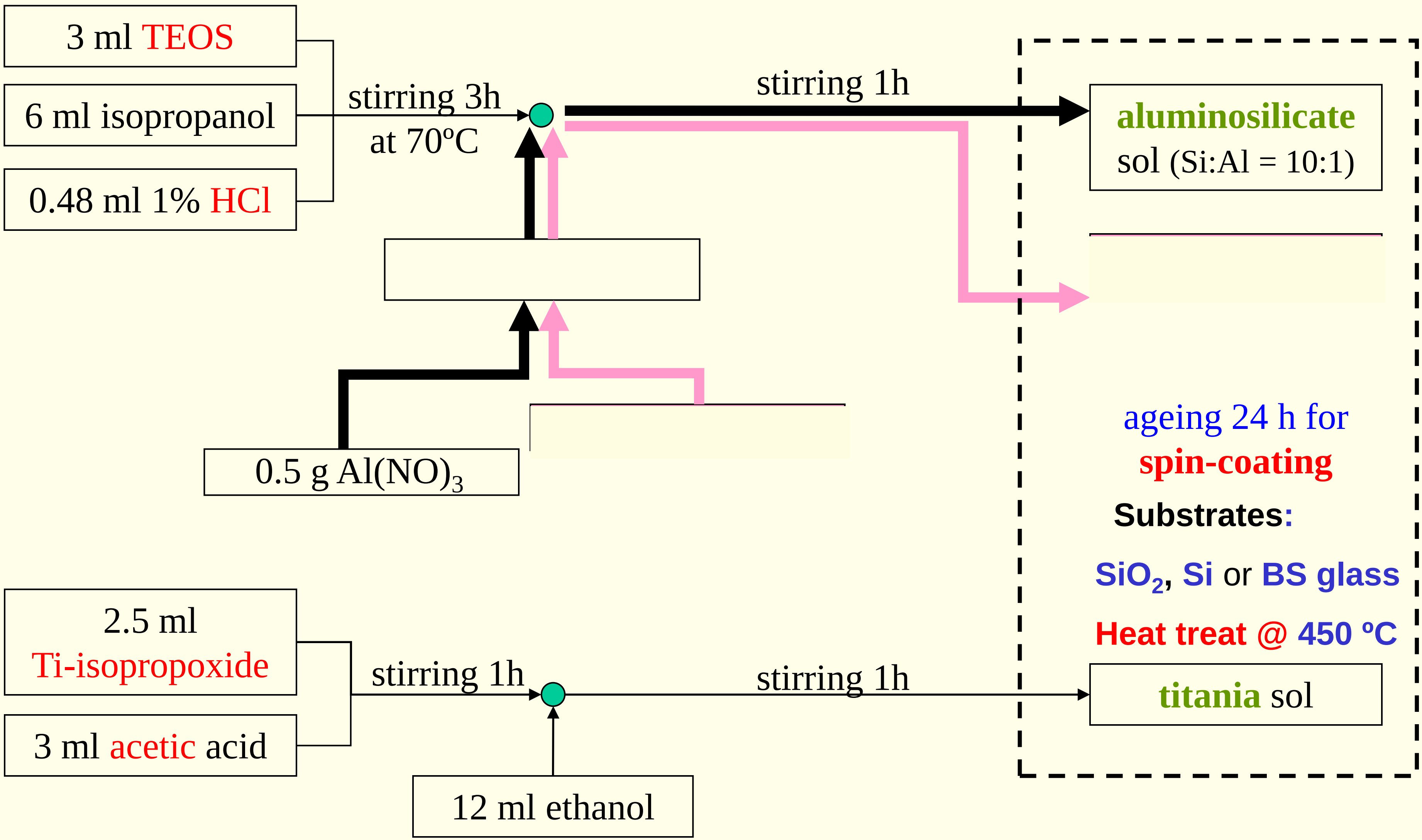


Si / (TS)$_4$ TMM simulation $n_S = 1.44$ $n_T = 2.0$

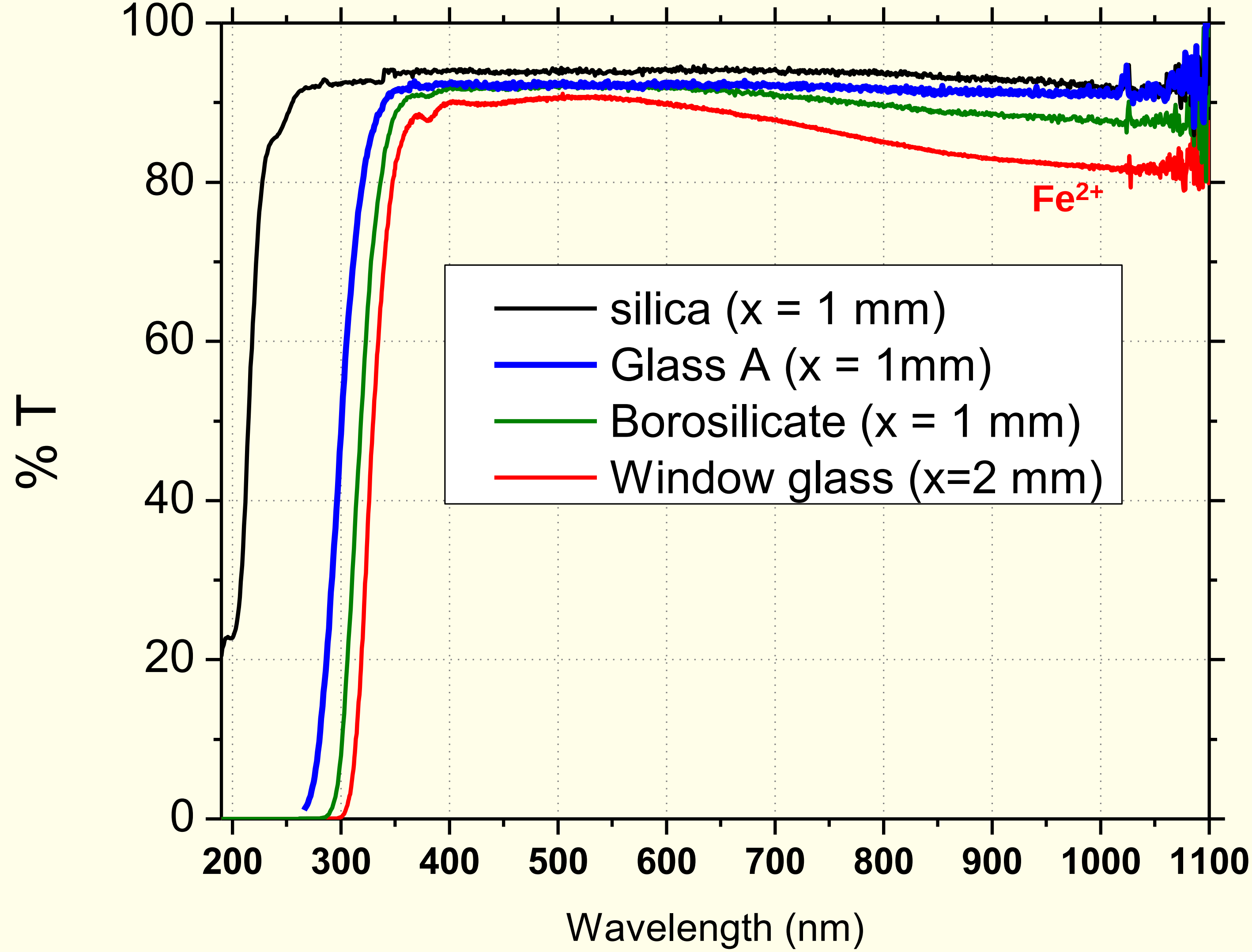
$x_S = 175$ nm $x_T = 125$ nm



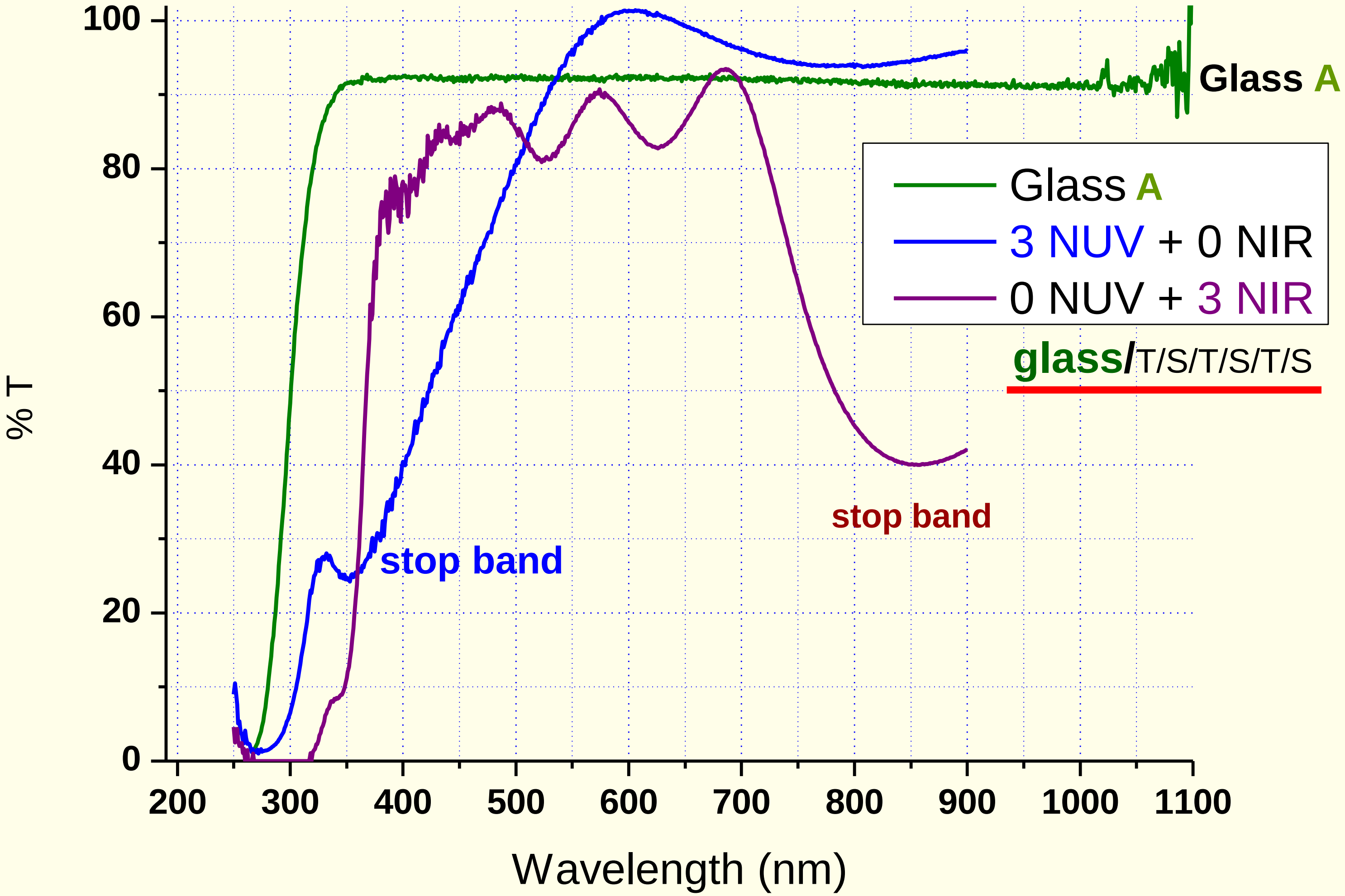
Sol-gel film processing



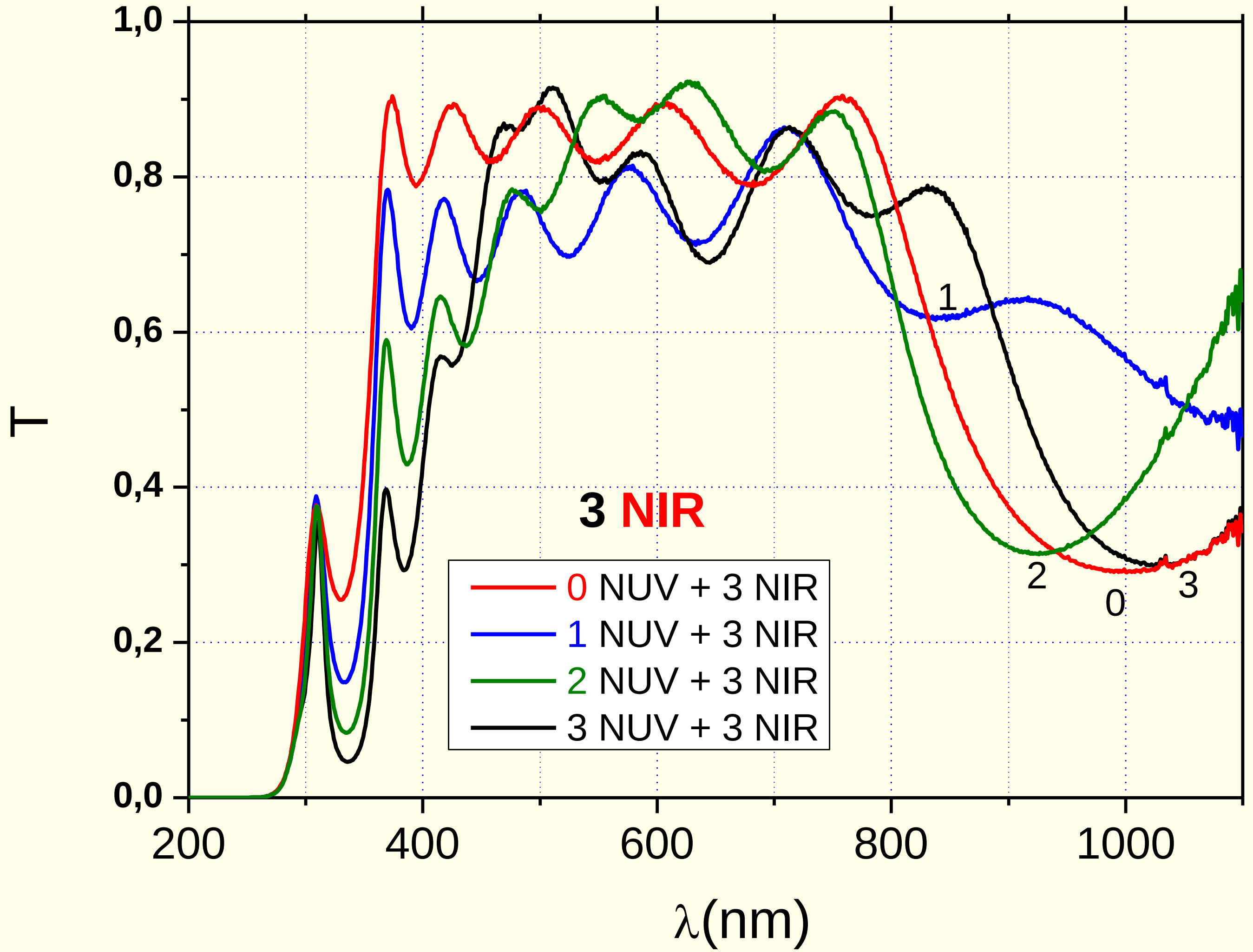
- Optical **transmission** of substrates



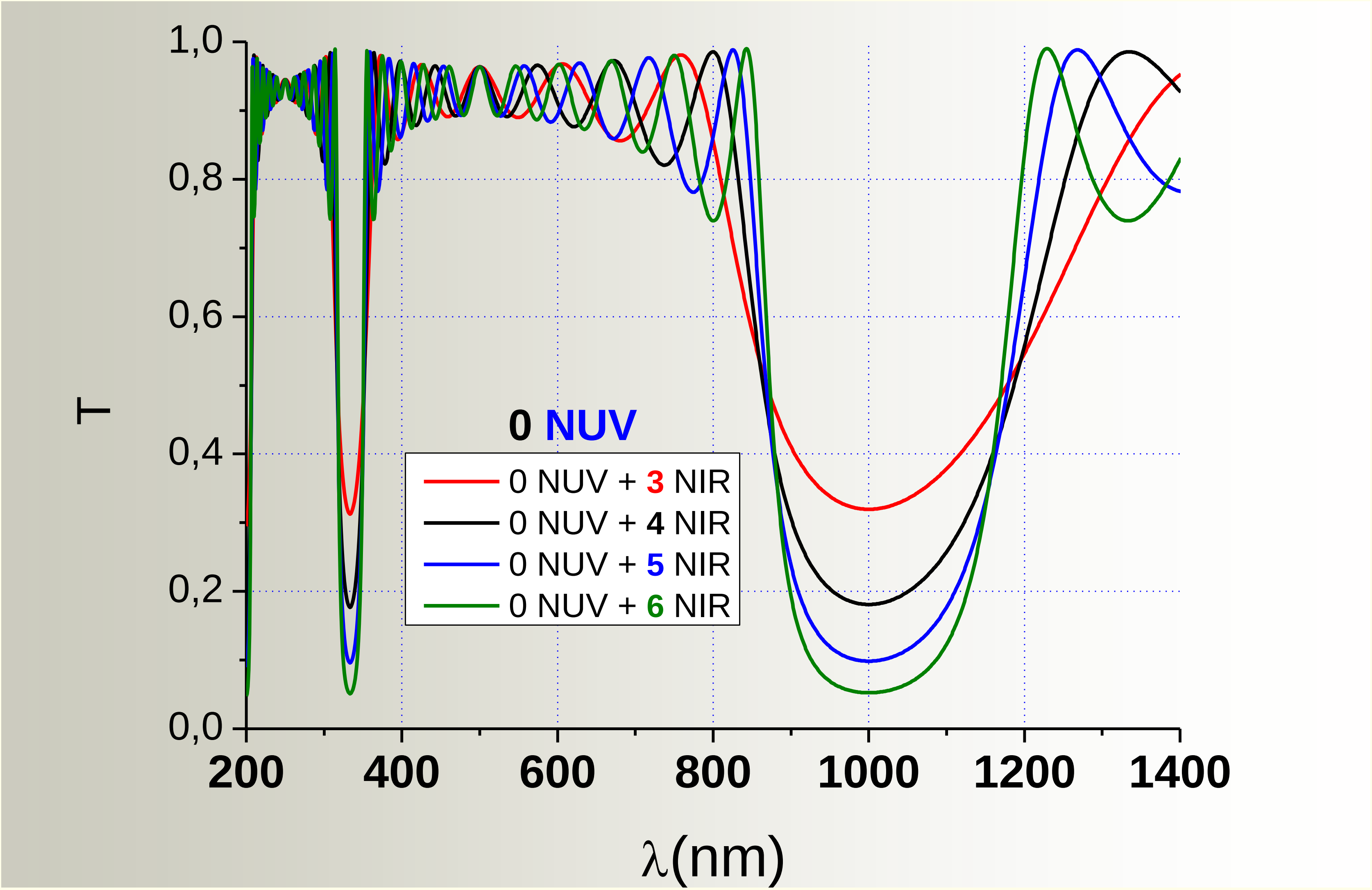
- Optical **transmission** of BMs (**NUV** and **NIR**)



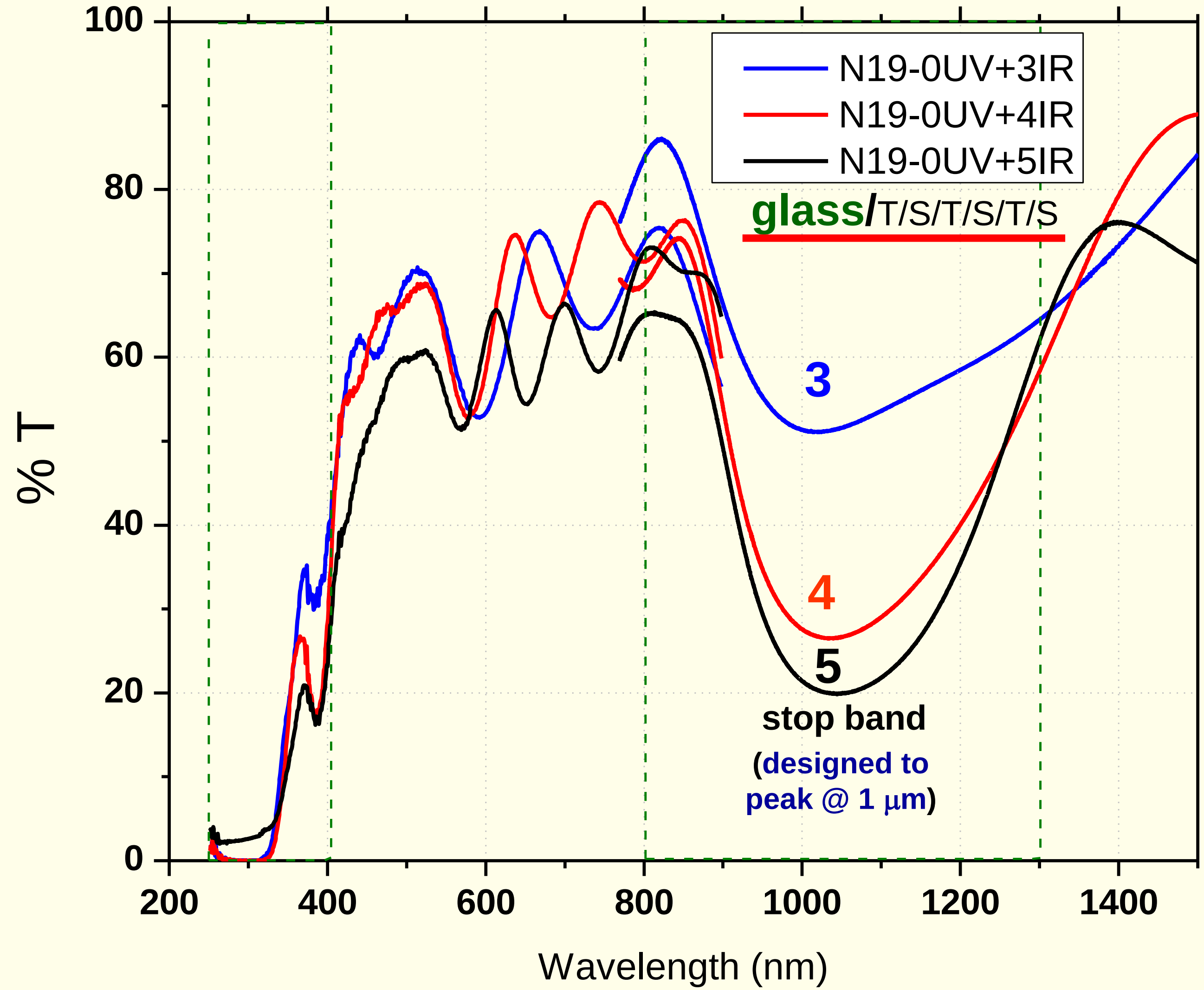
- Simulations of BMs spectral responses (NUV+NIR)



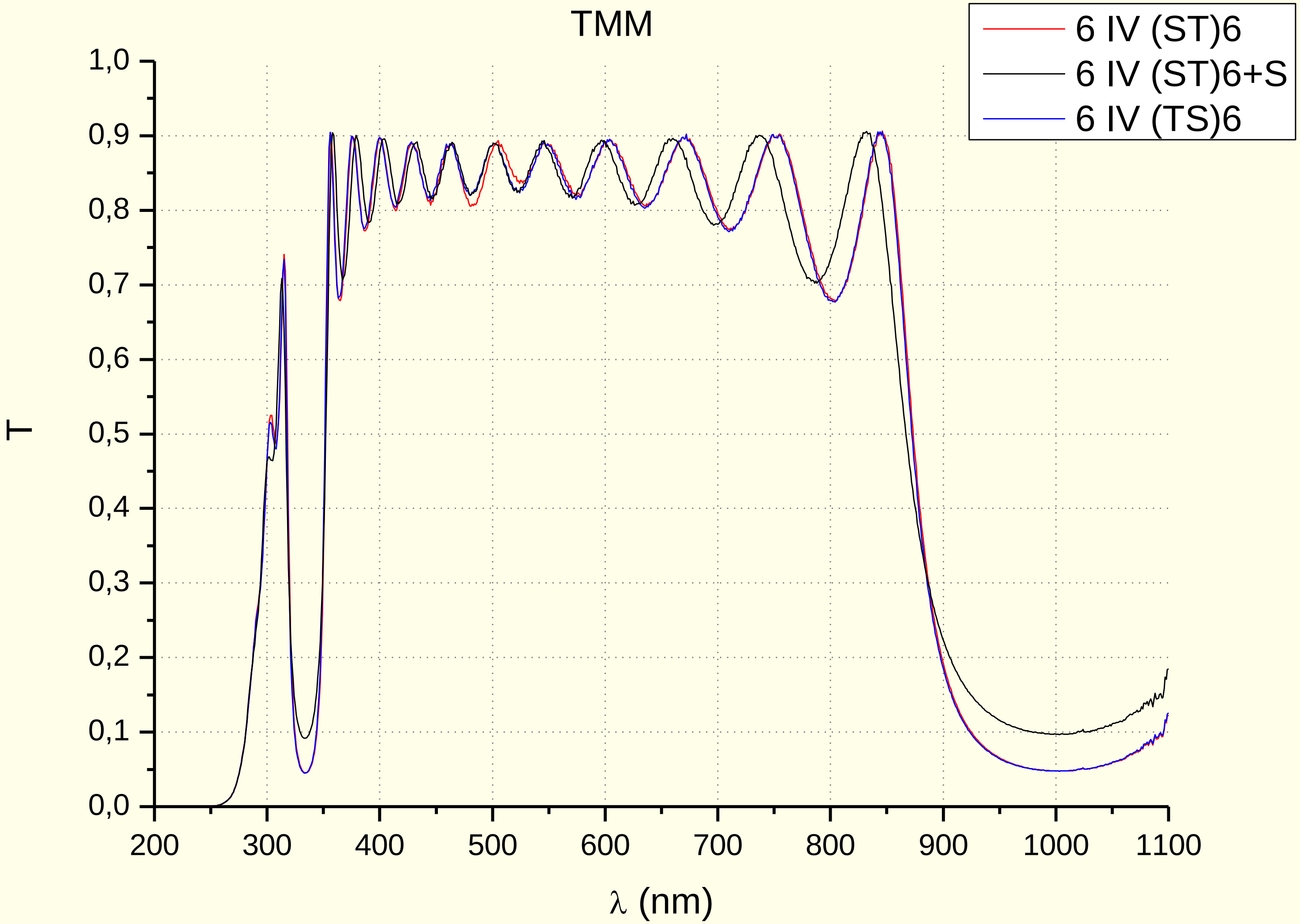
- Simulations of BMs spectral responses (**NIR**) – targeted to **1 µm**



- Optical **transmission** of BMs (**NIR**) 3 - 5 pairs



Simulation


TMM
6 IV (ST)6
6 IV (ST)6+S
6 IV (TS)6
T
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
200
300
400
500
600
700
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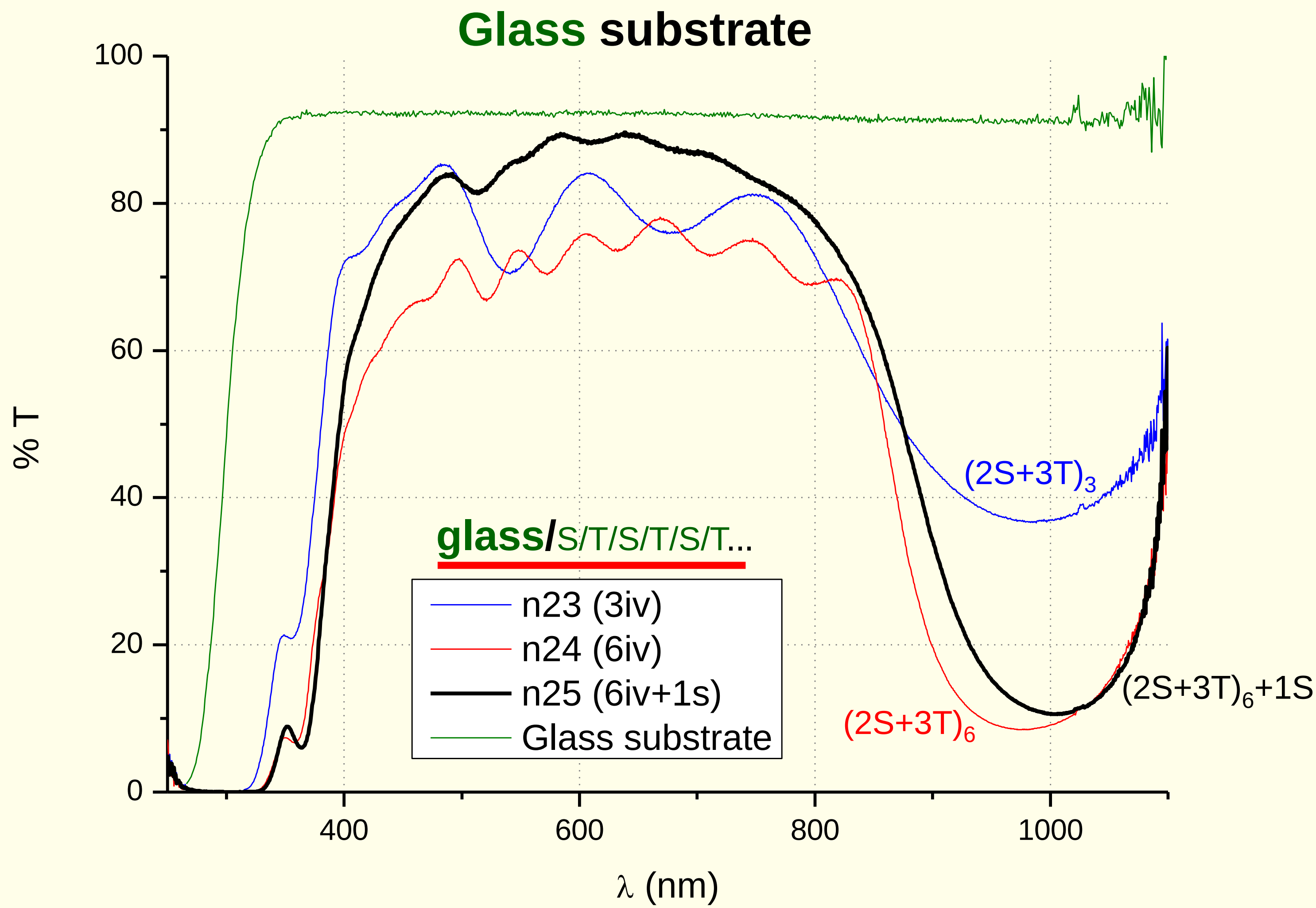
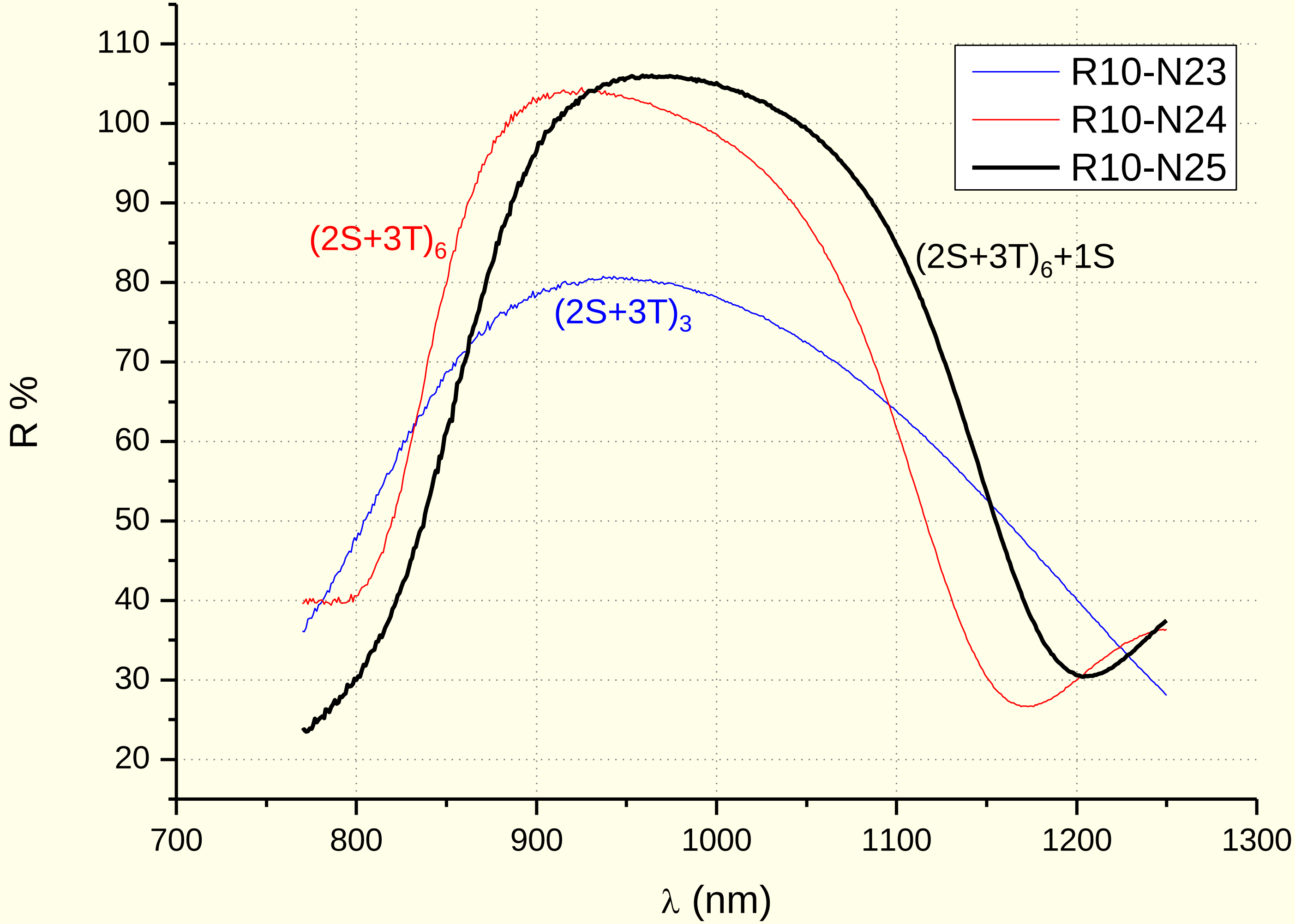
1100
λ (nm)



Nanostructured glass coatings for solar control

Reflection spectroscopy results



Conclusions

- A **solar control** coating reflects near-UV and near-IR radiation from the sun, while transmitting the visible portion.

- The **sol-gel** method is a low-cost coating technology for this purpose. Good quality **Bragg Mirrors** may be prepared by sol-gel processing.

- The combination of multiple types of coatings on the same glass offers a possibility to obtain **multi-functional** window glass.

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References:

Rui M. Almeida, Luís M. Fortes and M. Clara Gonçalves, "**Sol-Gel derived photonic bandgap coatings for solar control**", Opt. Mater. 33 (2011) 1867–1871.

Commercial glasses, Advances in Ceramics, Vol. 18, ed. D.C. Boyd and J.F. MacDowell, The American Ceramic Society (Columbus, Ohio, 1986).