Nanophotonic Approaches for Selective Absorption Enhancement

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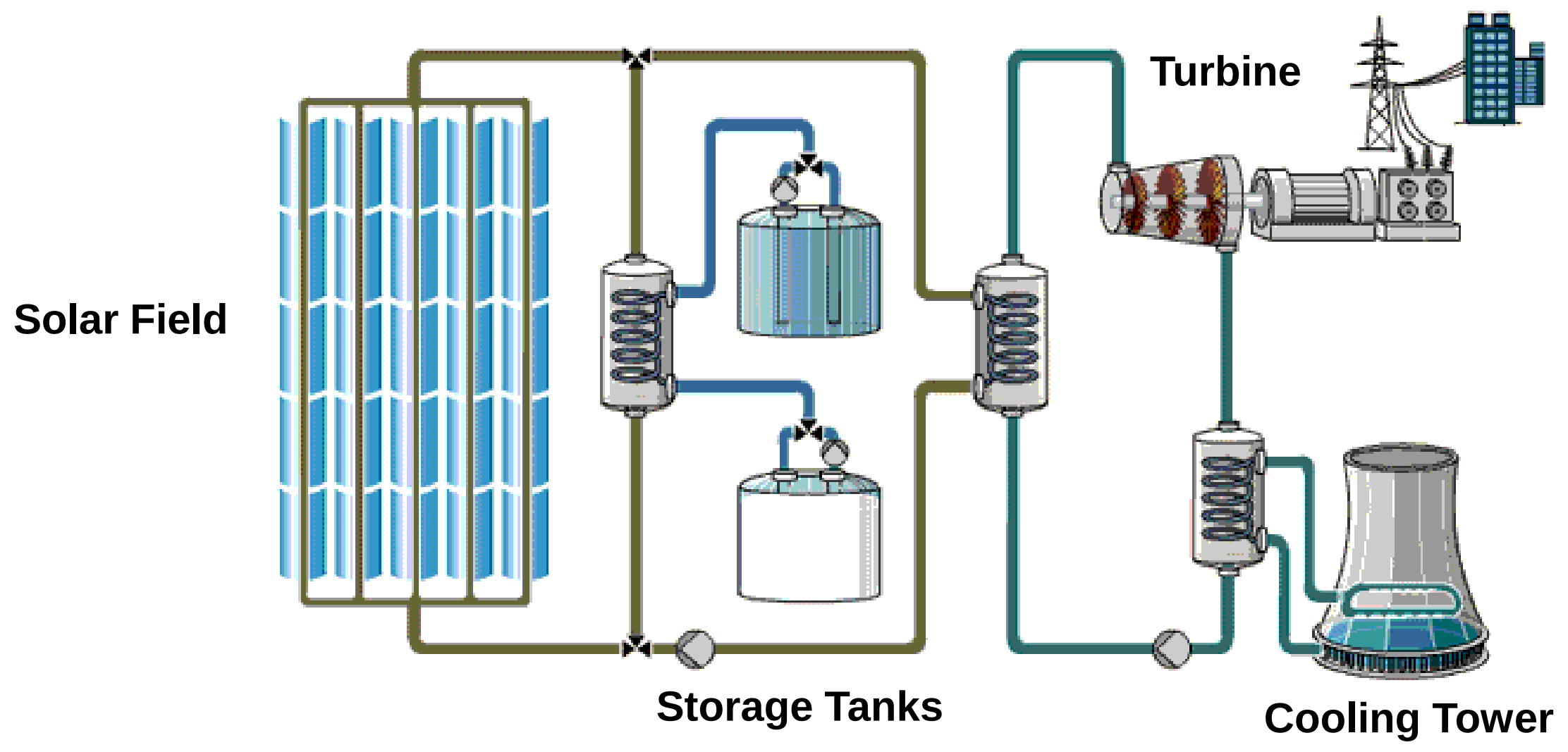
Introduction to Concentrated Solar Thermal (CST)

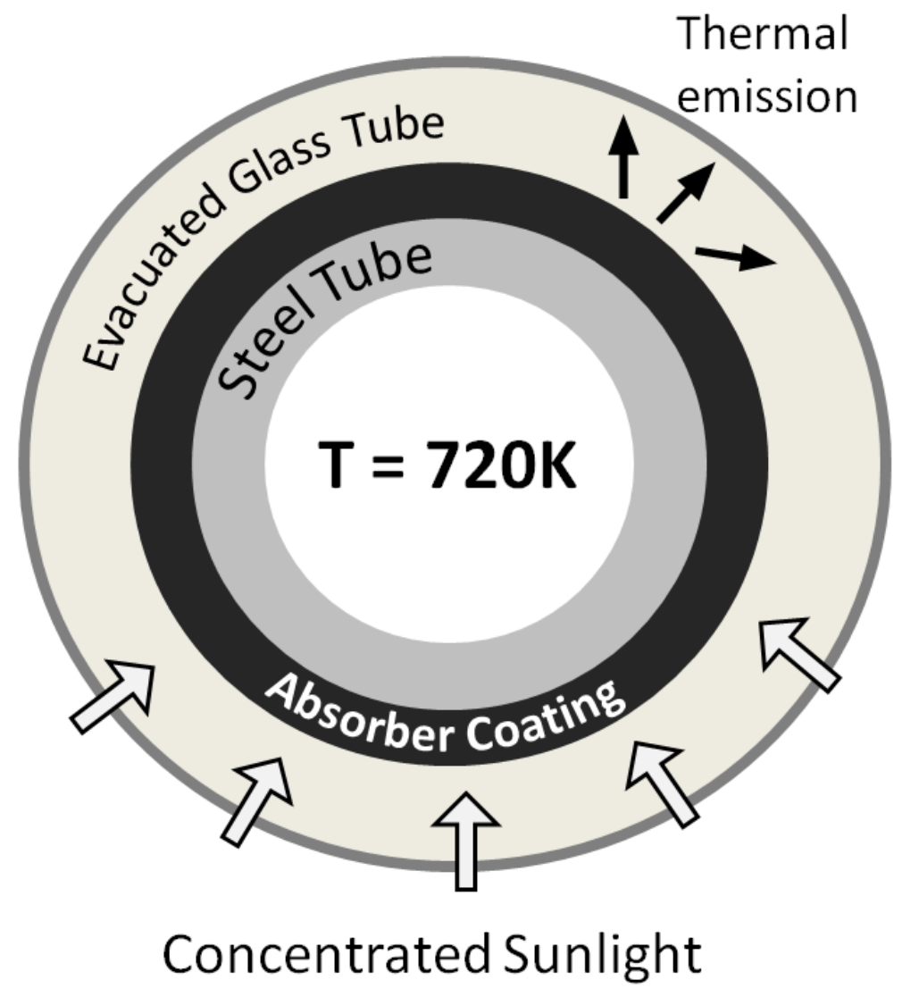
In the **trough configuration**, sunlight is concentrated by parabolic mirrors onto a heat collection element (HCE). The HCE is an absorber tube which runs along the focal point of the trough. The absorbed heat can be stored for several hours in thermal storage tanks. The heat can then be converted into steam to drive a turbine and generate electrical power.



Advantages of CST:

- Converts the **full spectrum** of solar radiation into heat.
- **Storage** capacity → High capacity factor (>40%)
- **Cost- effective**
- Lifetime > 20 years
- Effective for **large scale** generation (>50MW)
- Can supply steam for an industrial process or heating
- Can be used to **retrofit** an existing fossil fuel fired power plant

Optimizing a Solar-Selective Absorber



The heat collection element or absorber tube is coated with a solar-selective absorber which has two functions:

- **Maximize** the **solar absorptivity**
- **Minimize thermal emission** from its surface

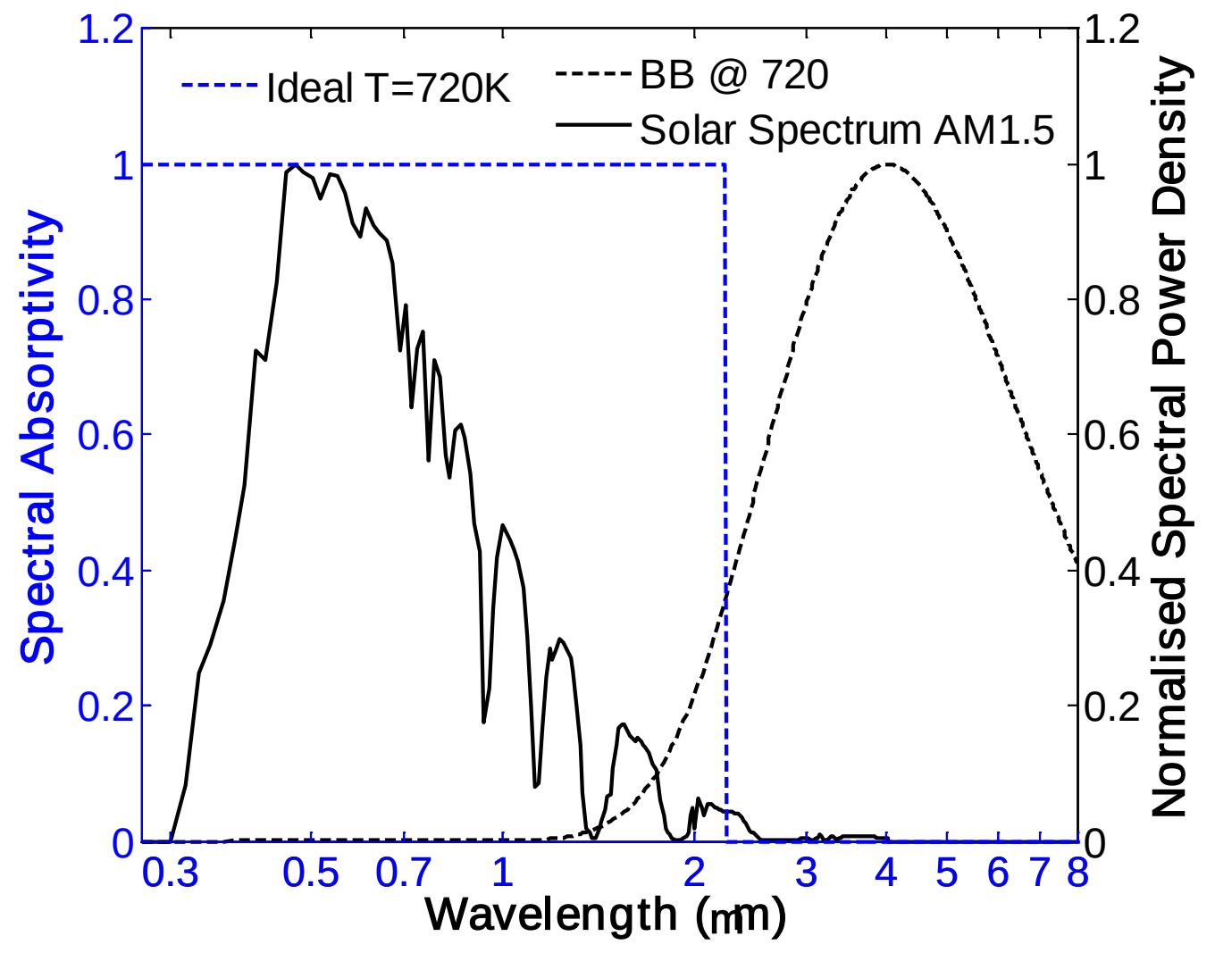


Fig. 1. Spectral absorptivity of an ideal absorber at T=720K with optimized cut-off frequency at 2.24 μm. Normalized power spectral densities for black body (BB) at 720K and solar spectrum (AM1.5G) are shown for illustration.

Solar Spectrum (AM1.5G) and black body (BB) radiation at 720K have little spectral overlap.

→ Opportunity for **Spectral Selectivity**

Ideal absorber

- Absorptivity **$\alpha=1$** for $\lambda < \lambda_c = 2.24\mu m$
- Emissivity **$\varepsilon=0$** for $\lambda > \lambda_c = 2.24\mu m$

Acknowledgment

The authors acknowledge support from **DOE** and **GCEP**.

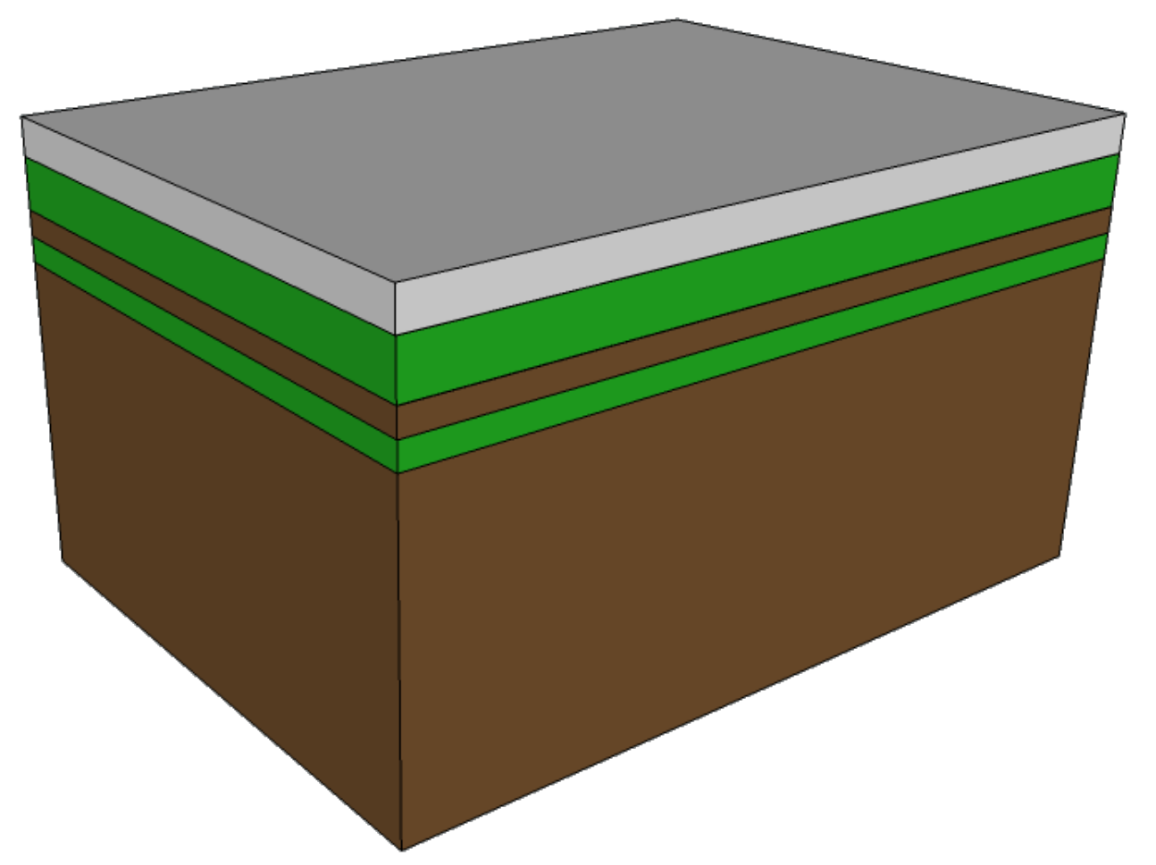
References

N. P. Sergeant, M. Agrawal and P. Peumans, *High performance solar-selective absorbers using sub-wavelength gratings*, **Optics Express**, Vol. 18, Issue 6, pp. 5525-5540 (2010)

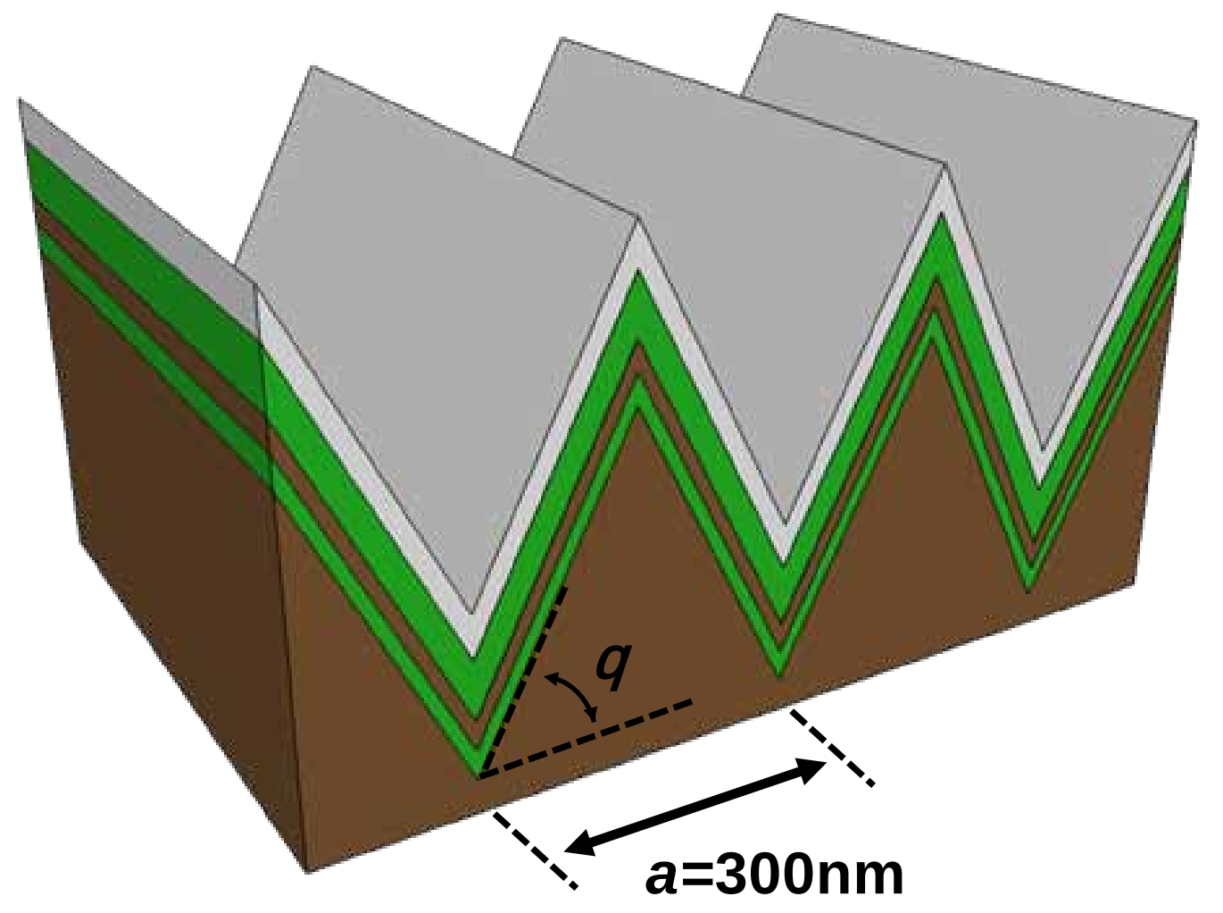
N. P. Sergeant, O. Pincon, M. Agrawal and P. Peumans, *Design of wide-angle solar-selective absorbers using aperiodic metal-dielectric stacks*, **Optics Express**, Vol. 17, Issue 25, pp. 22800-22812 (2009)

Design of Metal-Dielectric Stacks

Planar Substrate

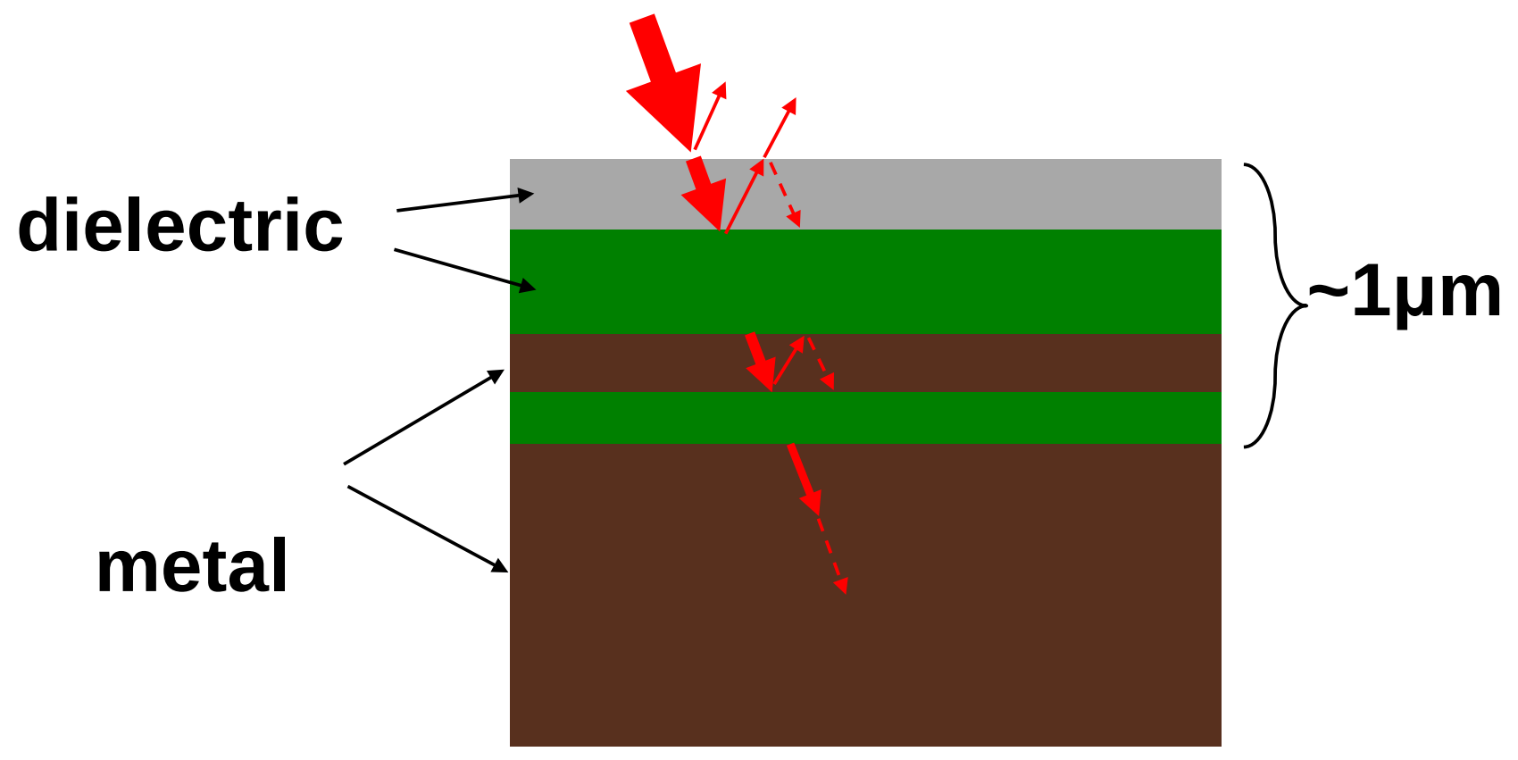


V-groove Substrate



Exploiting interference effects

When light is incident on a metal-dielectric stack, it is reflected and transmitted at every interface. The metallic absorbing layers are spaced by dielectric layers creating constructive interference and resonant cavities to enhance absorption at specific wavelengths.



Impedance Matching

A sub-wavelength grating (SWG) provides an impedance matching mechanism, since the refractive index changes gradually from air to that of the bare metal. This enhances absorption for wavelengths of the order of the grating.

Simulation Results – High Spectral Selectivity

We simulated stacks on planar substrates using the **transfer-matrix method** and optimized them with a **needle optimization** technique. We used **Mo** as metal, and **MgF_2** and **TiO_2** as the dielectric spacer layers. Layer thicknesses vary from 5 to 100nm. We simulated the coated V-groove gratings using **RCWA.** The period *a*=300nm was kept constant and the optimal V-groove angle θ was determined for every coating under consideration

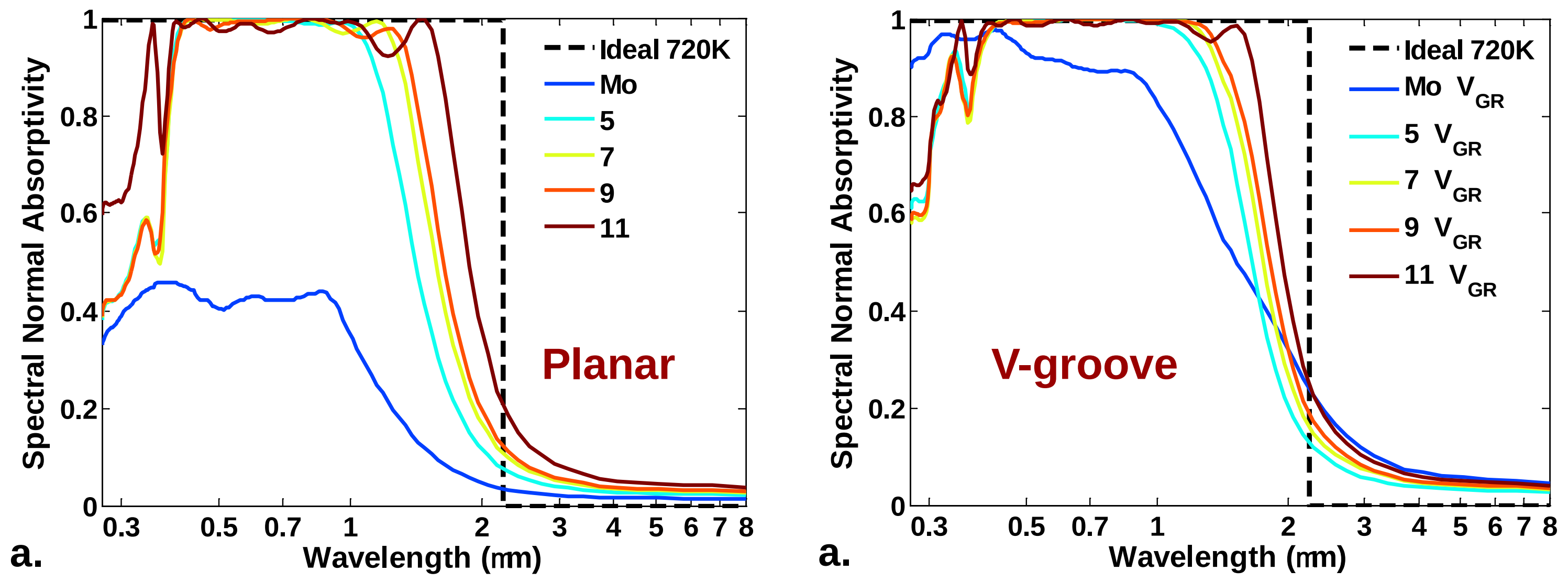


Fig. 2. Modeled spectral absorptivity at normal incidence for aperiodic metal-dielectric stacks optimized using Mo, TiO_2 and MgF_2 on (a) planar substrates and (b) V-grooved substrates. The optimized stacks have respectively 5 (cyan), 7 (yellow), 9 (orange) and 11 (brown) layers. The spectral absorptivity of an ideal absorber at 720K is also plotted for comparison. For the V-groove substrate the period a=300nm was kept constant and the optimal V-groove angle was determined for every coating.

Wide Angle Tolerance

Because the absorption enhancement occurs over a wide spectral range from 300nm to 2000nm, the stack design is also more tolerant to angular variation from normal incidence up to 75° off-normal. The metal-dielectric stacks are therefore excellent candidates for **wide-angle** solar-selective absorbers.

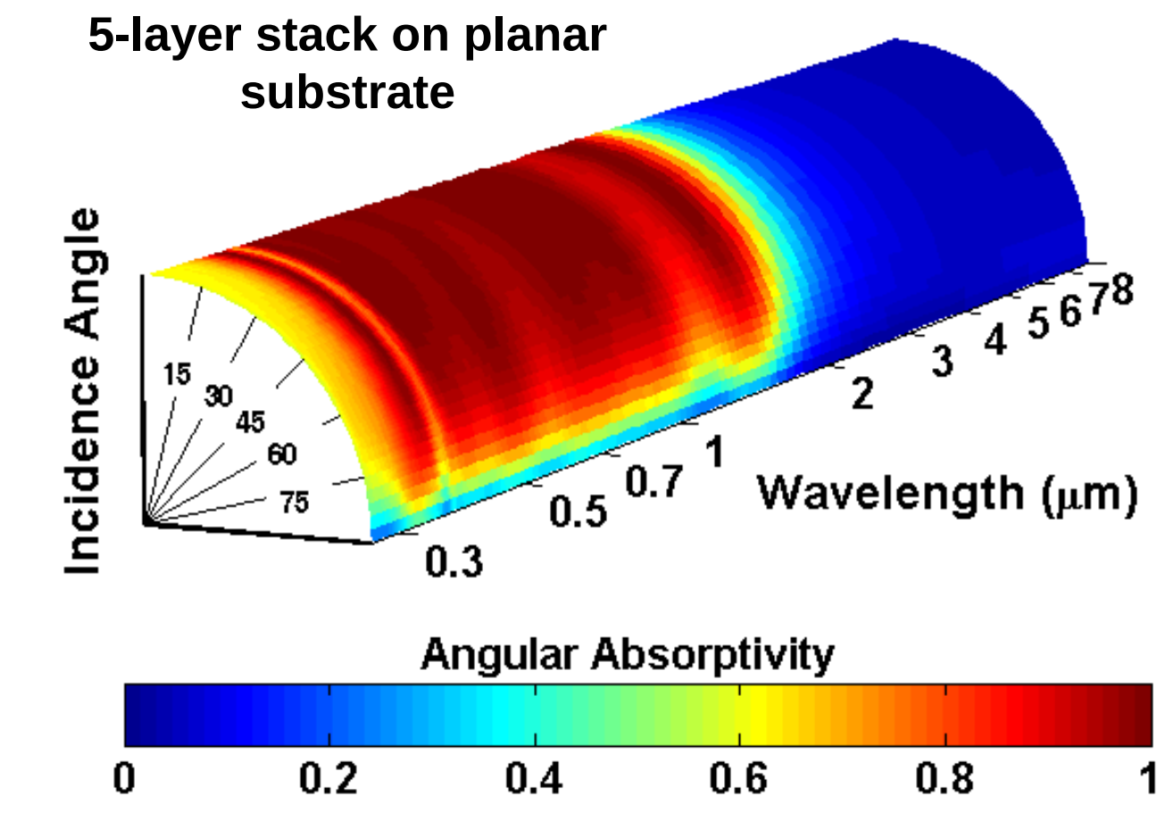


Fig. 3. Modeled spectral directional absorptivity of the 5-layer coating using layers of Mo, TiO_2 and MgF_2 optimized for operation at 720K.

Fabrication of Metal-Dielectric Stacks

Fabrication Technique

A 5-layer spectrally selective coating, composed of Mo, TiO_2 and MgF_2 was deposited using a combination of RF sputtering (Mo and TiO_2) and e-beam evaporation (MgF_2). The resulting coating was investigated using cross-sectional TEM to determine the thicknesses of the resulting films.

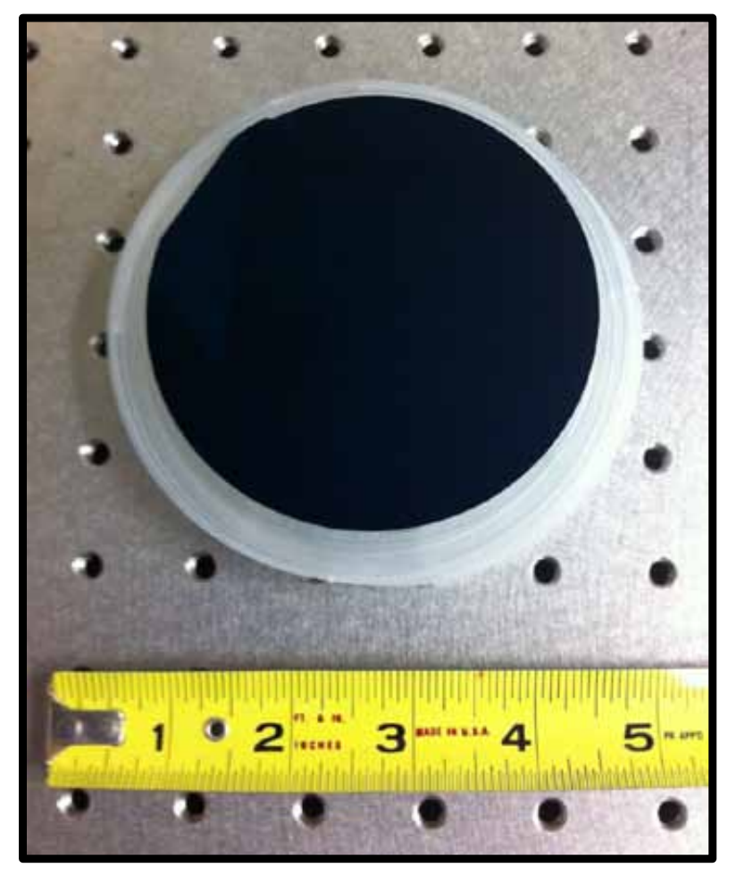


Fig. 4. Picture of the 5-layer coating composed of MgF_2, TiO_2 and Mo deposited on a 4" Fused Silica (FS) wafer.

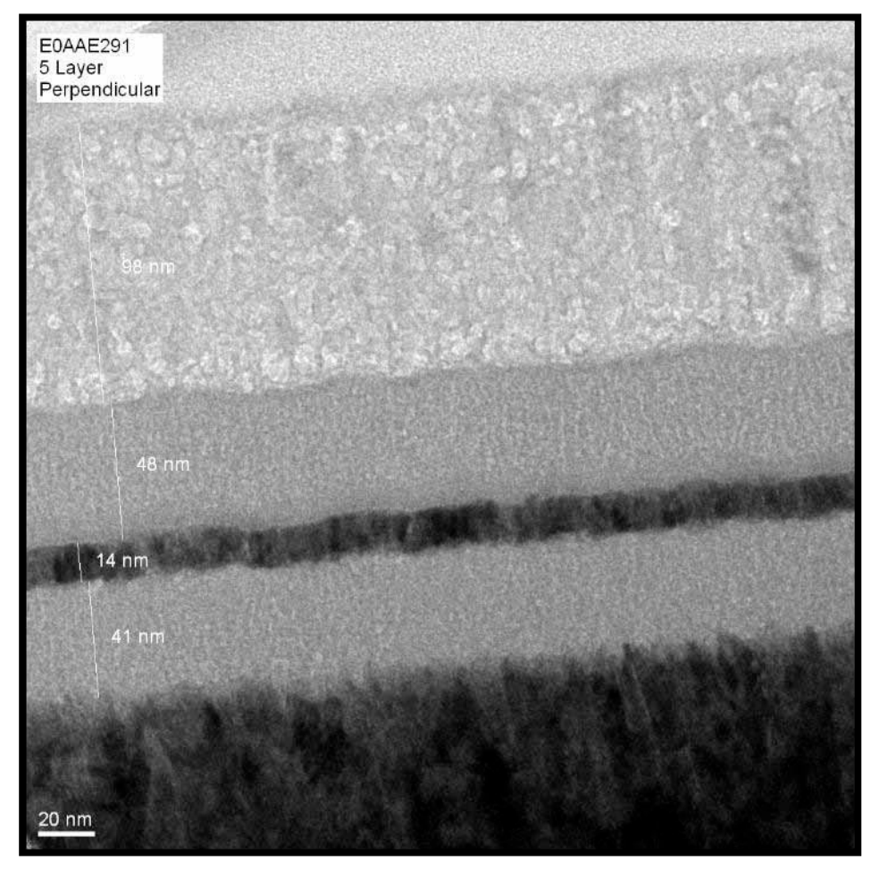


Fig. 5. Cross-sectional TEM of the 5-layer coating composed of MgF_2, TiO_2 and Mo, indicating the thicknesses of each layer inside the coating.

XPS depth profile

To further investigate the properties of the coating, we have performed XPS depth profiling. We can study the elemental composition as a function of depth by performing XPS after a specific sputtering interval. The experiment confirms the oxidation state and elemental composition of the layers.

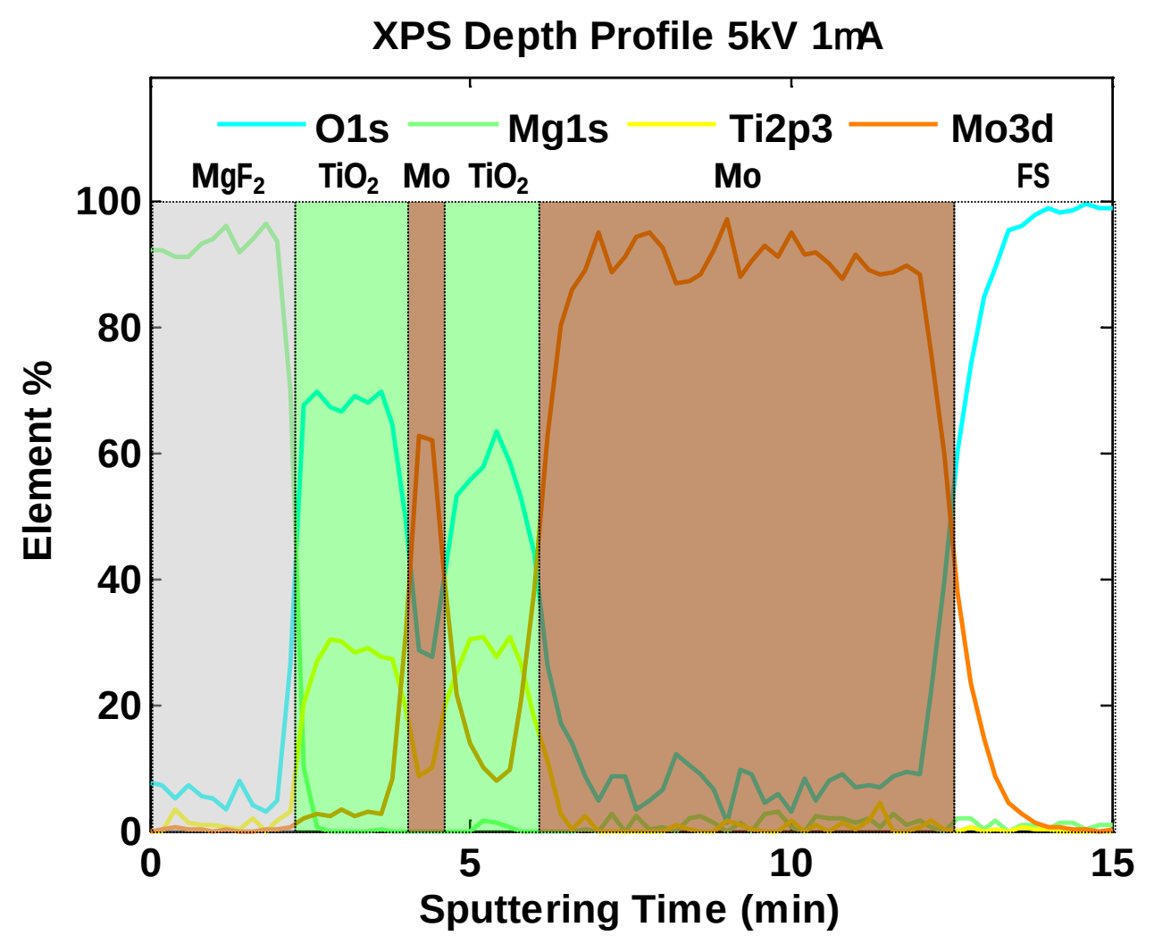


Fig. 6. Depth profile showing the relative elemental profile for Mo, O, Mg and Ti of the 5-layer solar-selective absorber stack. As only Mg was considered, the relative elemental concentration of Mg is close to 100 in this case first layer.

Spectral Absorptivity

The spectral reflectivity (R) of the solar-selective coating was measured at room temperature in a Fourier transfer infrared spectrometer (FTIR) which is capable of measuring the spectral properties of the film over a wide spectral range from 300nm up to 8μm. Good spectral selectivity was achieved in agreement with the model. These aperiodic metal-dielectric stacks are well suitable for solar selective coatings in future solar thermal conversion systems.

Table 1. AM1.5G weighted absorptivity (α_{solar}) and thermal emissivity ($\varepsilon_{thermal}$) at 720K for the measured 5-layer solar-selective coating compared to the predicted properties from transfer matrix algorithm.

5-layer Coating	α_{solar}	$\varepsilon_{thermal}$ 720K
Modeled	0.88	0.03
Measured	0.83	0.14

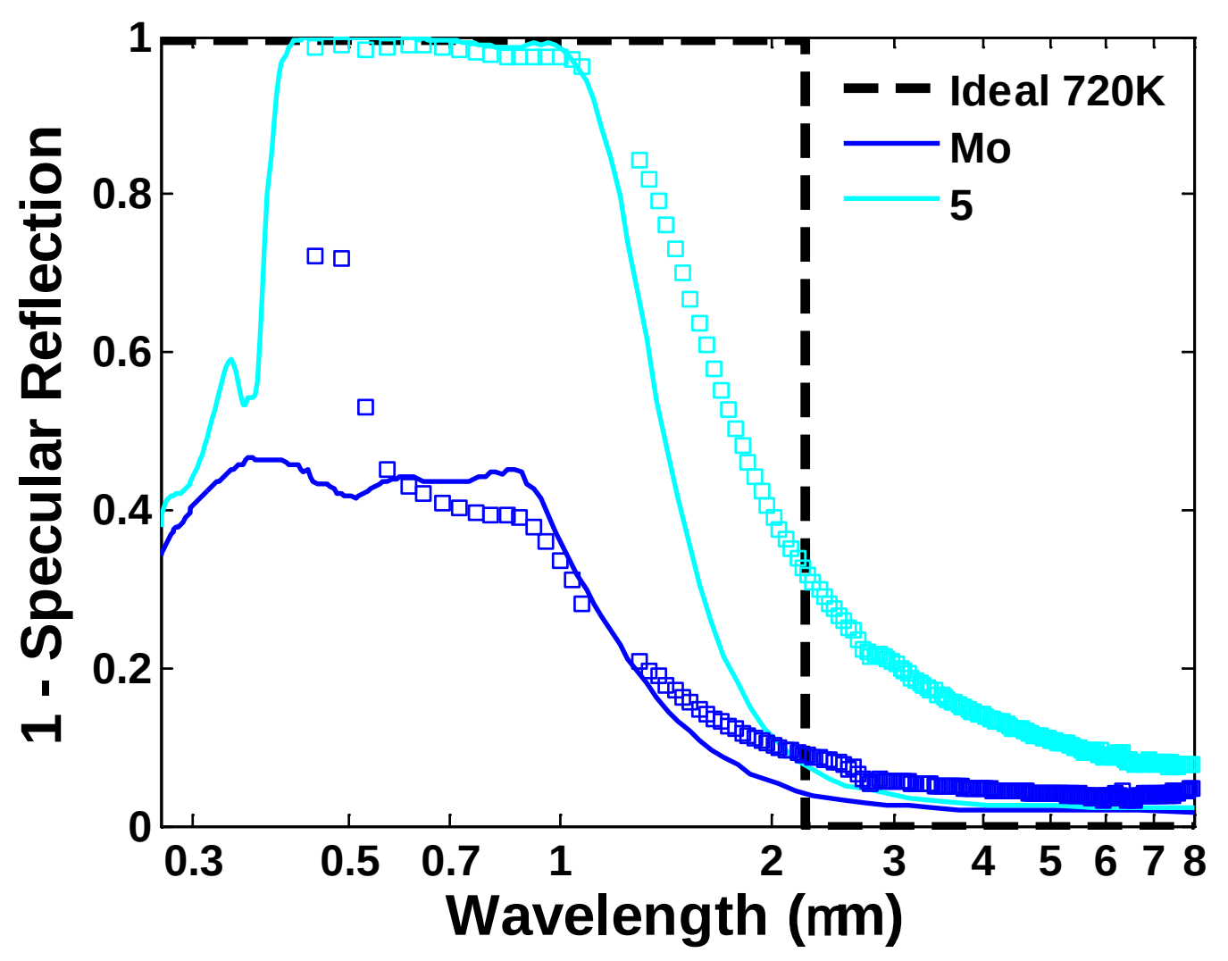


Fig. 7. Measured (markers) and modeled (curves) 1-R (equivalent to spectral absorptivity) at 10° angle of incidence for the 5-layer aperiodic metal-dielectric stacks (cyan) optimized using Mo, TiO_2 and MgF_2 on planar substrates. The spectral properties of the bare Mo mirror (blue) is also show as a reference. Excellent agreement is obtained for the 5-layer coating in the spectral range 0.5μm to 1.5μm. The loss is sharpness is attributed to roughness of the stack, which leads to increased absorptivity in the NIR.

Conclusion

Optimal coatings for **planar geometry** were modeled to have a **thermal emissivity <10%** at 720K while **absorbing >94%** of the incident light. The **coated sub-wavelength V-groove gratings** can further enhance the absorptivity while still keeping low **thermal emissivity.**

Solar-selective coatings were fabricated using **sputtering and e-beam evaporation**. Their structural and spectral properties were characterized and good agreement was obtained between the measurement and the model. These aperiodic metal-dielectric stacks have **excellent spectral selectivity** and are thus good candidates for next generation solar thermal absorbers.