Photonic Innovations
Lab UCL

Multilayer vanadium dioxide nanocomposites for energy saving applications

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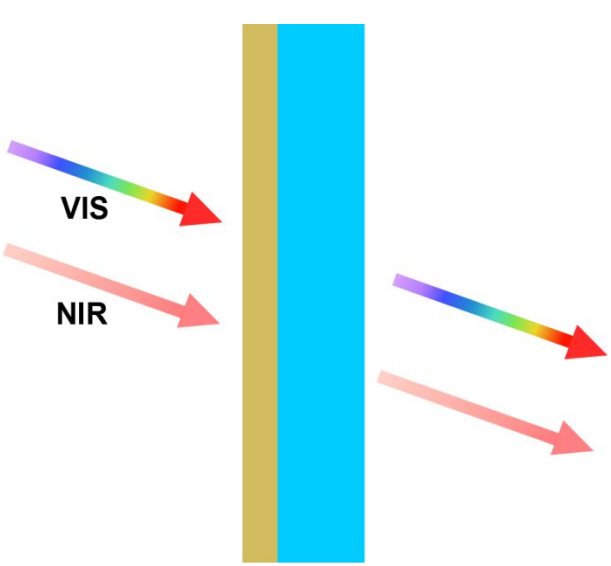
Outline:

- Introduction to vanadium dioxide smart windows
  - Review: thin film vs nanoparticle morphology
- Results:
  1. A thought experiment: What are the limits of thin film performance?
  2. Practical multi-layered coating surpassing previous records of performance
- Summary & next steps

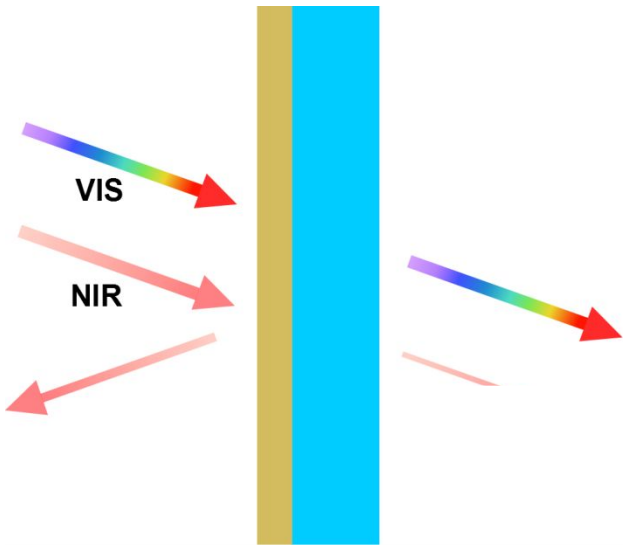
Vanadium dioxide smart windows

– Principle of operation

Cold weather



Hot weather

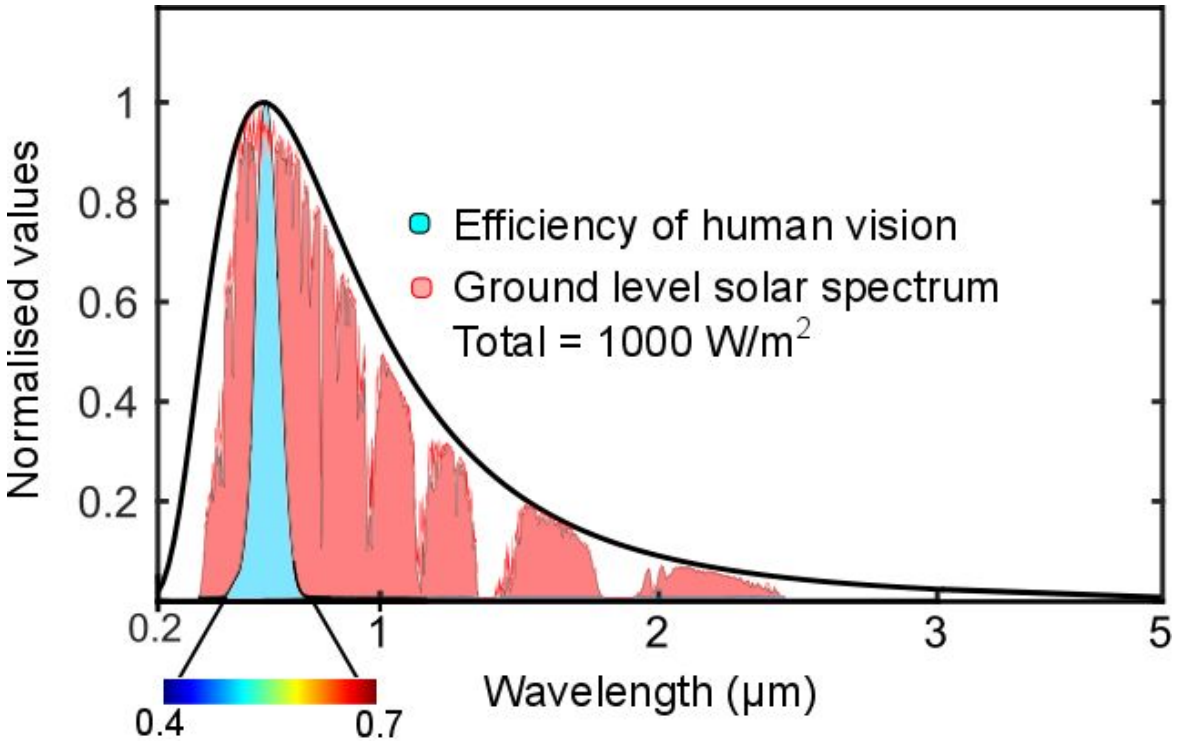


Properties required:

- Transmissive to both visible and infrared light (semiconducting - monoclinic)
- Transmissive to only visible light (metallic - rutile)

Vanadium dioxide smart windows

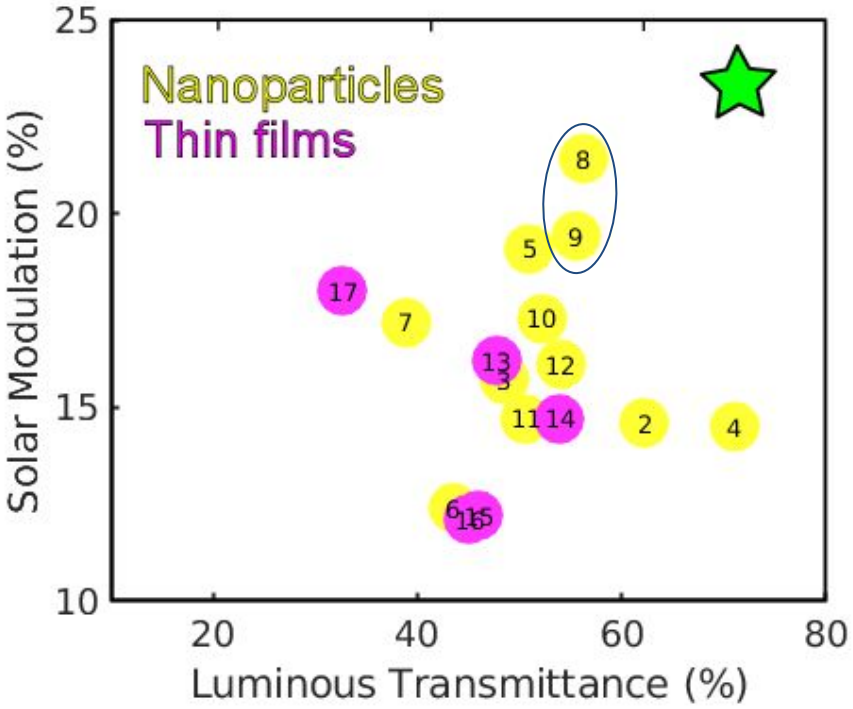
– Quantifying performance



Luminous transmission:
Cold state transmittance, weighted to human vision efficiency --- >60% desired for most buildings

Solar modulation:
Difference between hot and cold state transmittance, weighted to solar spectrum

Review: thin films vs nanoparticles



State of the art:

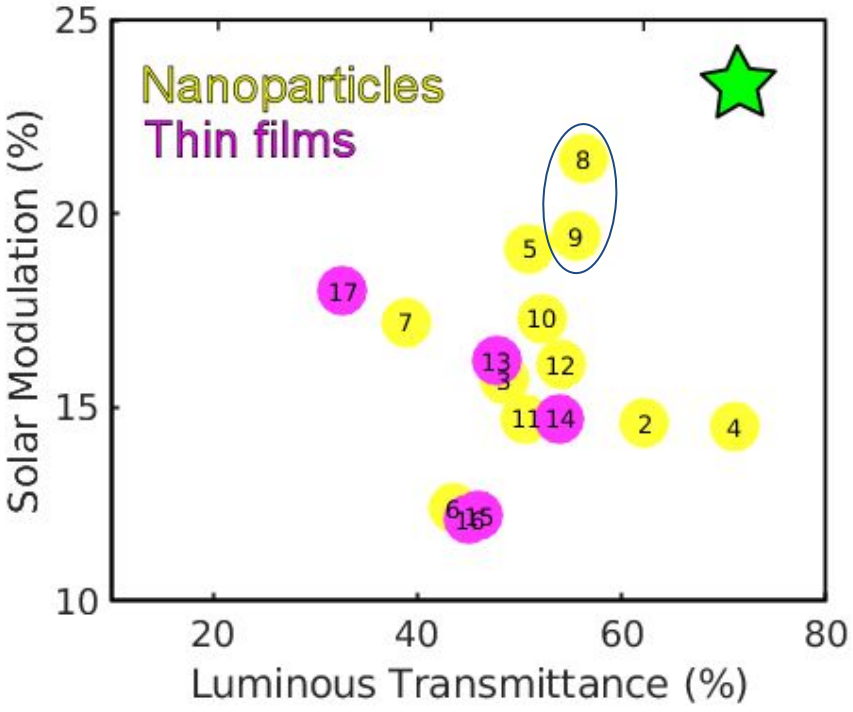
Nanoparticles

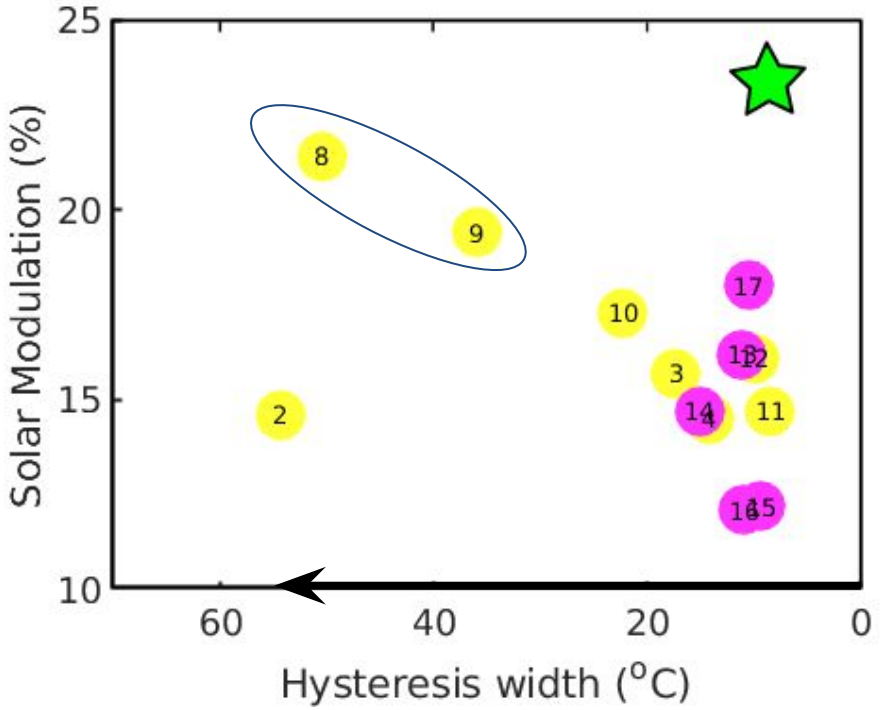
[8, 9] ACS Appl. Mater. Interfaces 2015, 7, 50, 27796-27803

Thin film

[13, 14] https://doi.org/10.1016/j.nanoen.2017.11.061

Review: thin films vs nanoparticles





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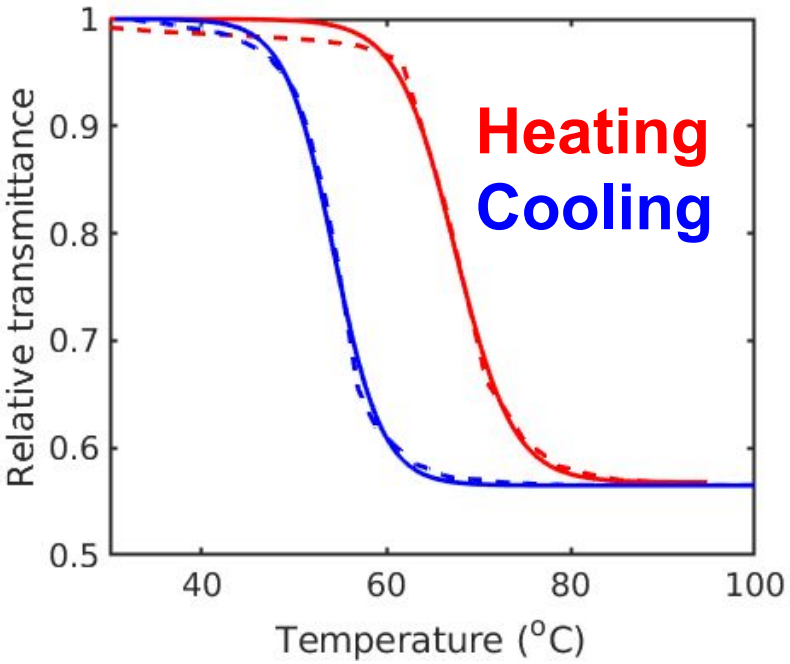
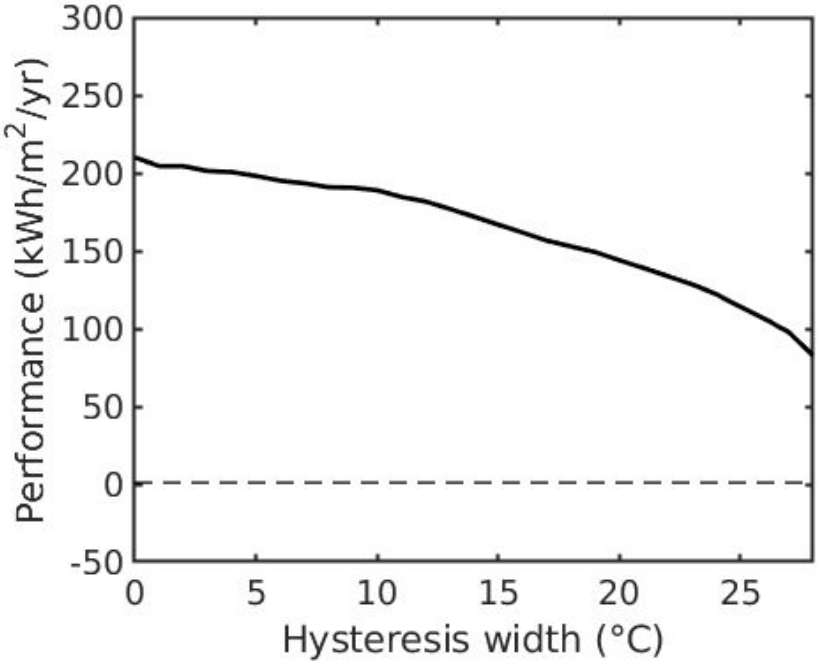
- Thin films are favourable for narrow hysteresis
- However solar modulation is typically lower

What is the effect of hysteresis?





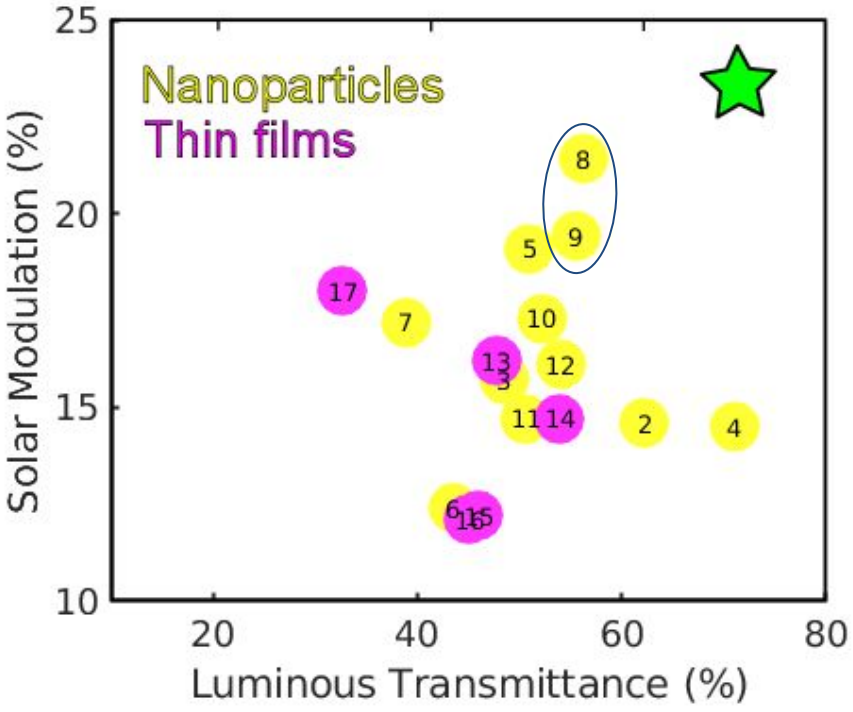
Example: Performance drop of > 50 % for hysteresis widths of 25 °C

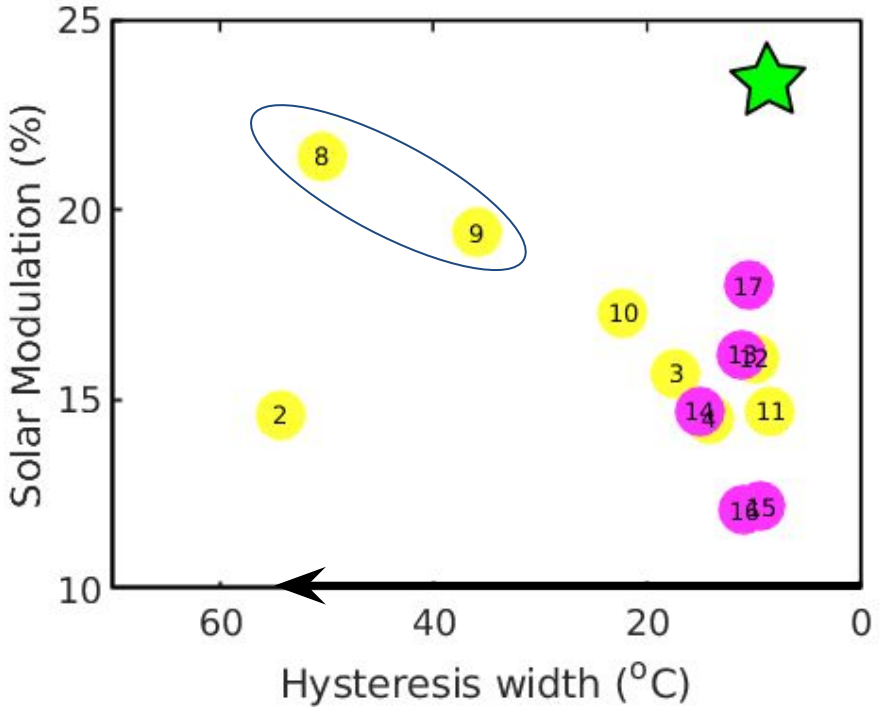
Hysteresis is always detrimental however the losses are dependent on many factors

Additionally hysteresis gradient should be sharp

Scientific Reports **volume 8**, Article number: 13249 (2018)

Review: thin films vs nanoparticles





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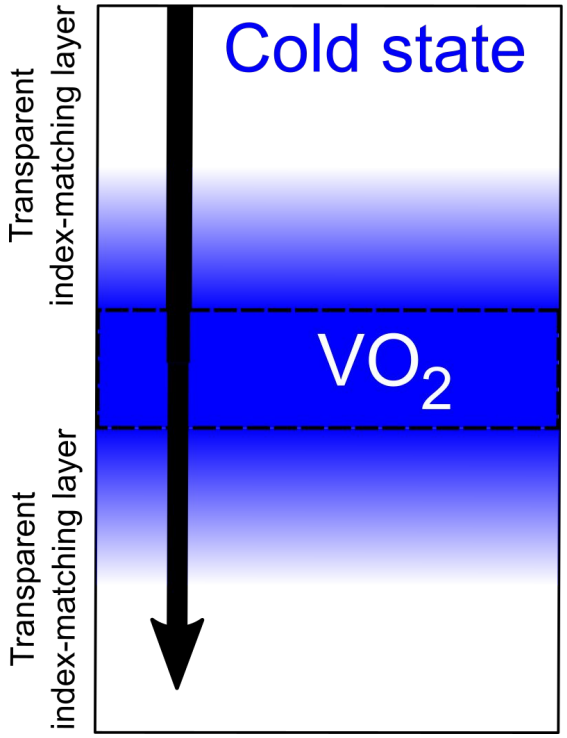
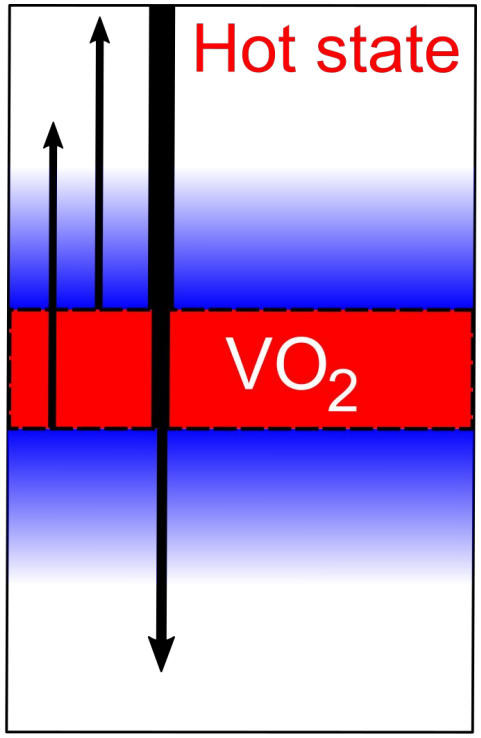
- Thin films are favourable for narrow hysteresis
- However solar modulation is typically lower

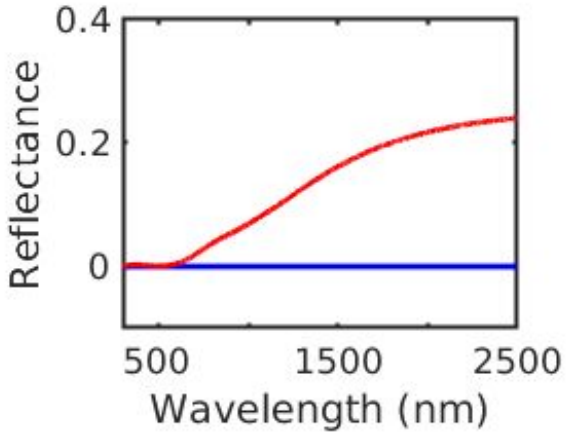
Can thin films do better?

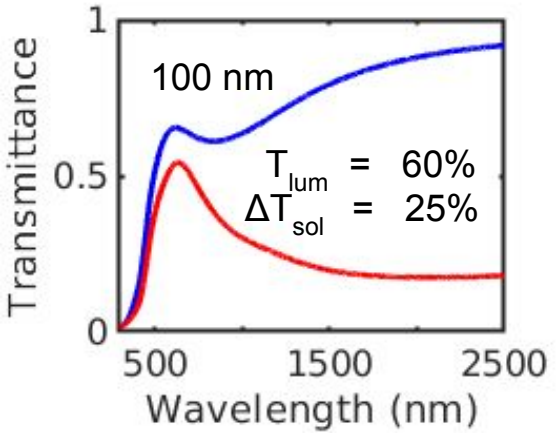
Thought experiment: what are the limits of thin film vanadium dioxide?

Index matching layers between air and cold state permittivity



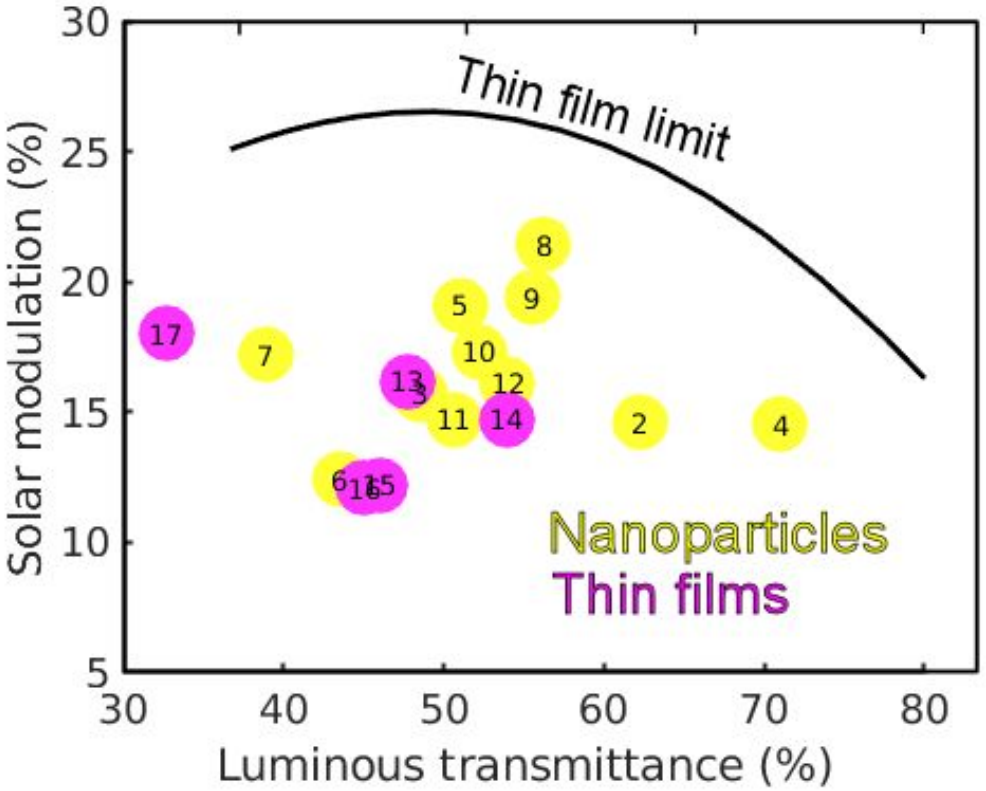






Thought experiment: what are the limits of thin film vanadium dioxide?

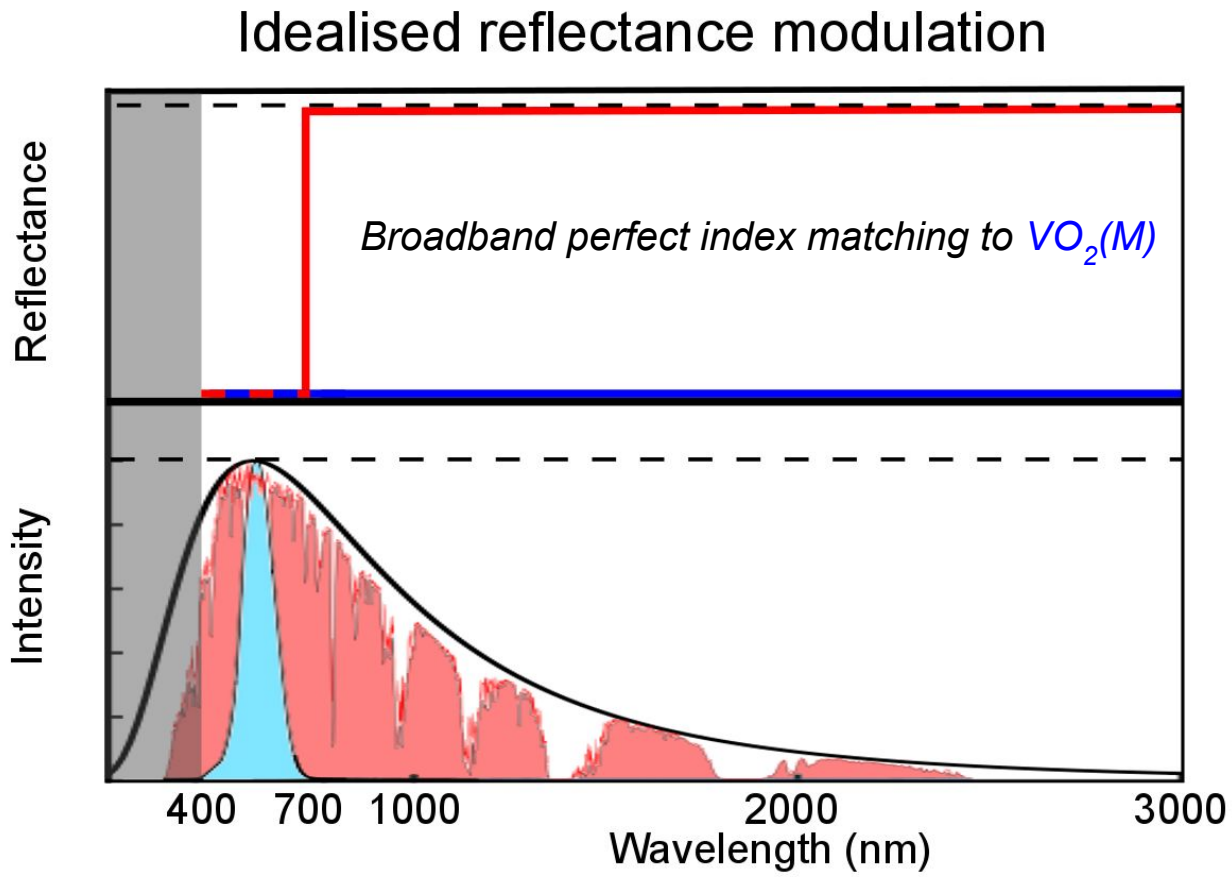
Performance calculated for a range of thicknesses (50 - 200 nm)



Lots of work to be done!

It's difficult to fabricate perfect index matching layers - can we design something more practical?

Practical design considerations

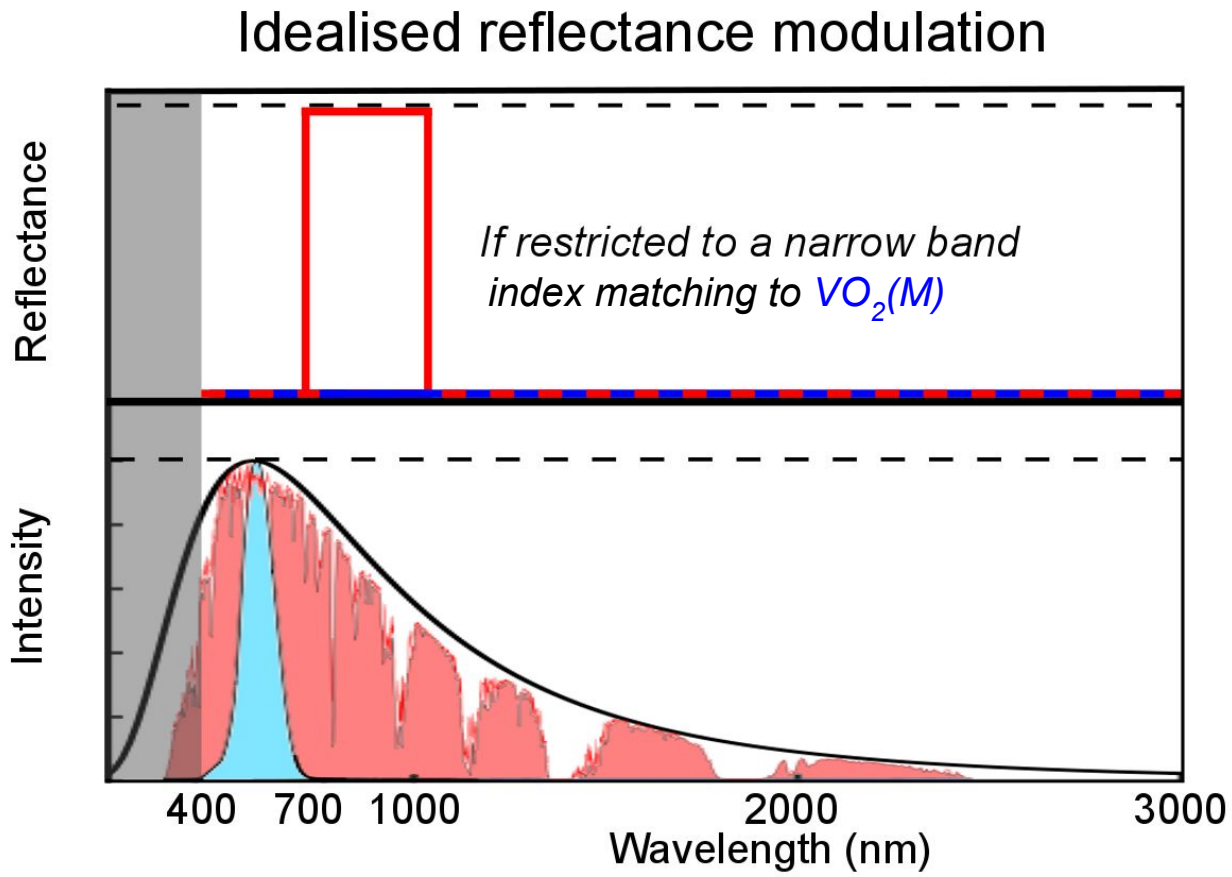


Would require graded index materials or nanostructures

Difficult to achieve!

Desired properties:
Minimal visible reflectance in both states (400 - 700 nm)
Large modulation in the IR (700 - 2500 nm)

Practical design considerations

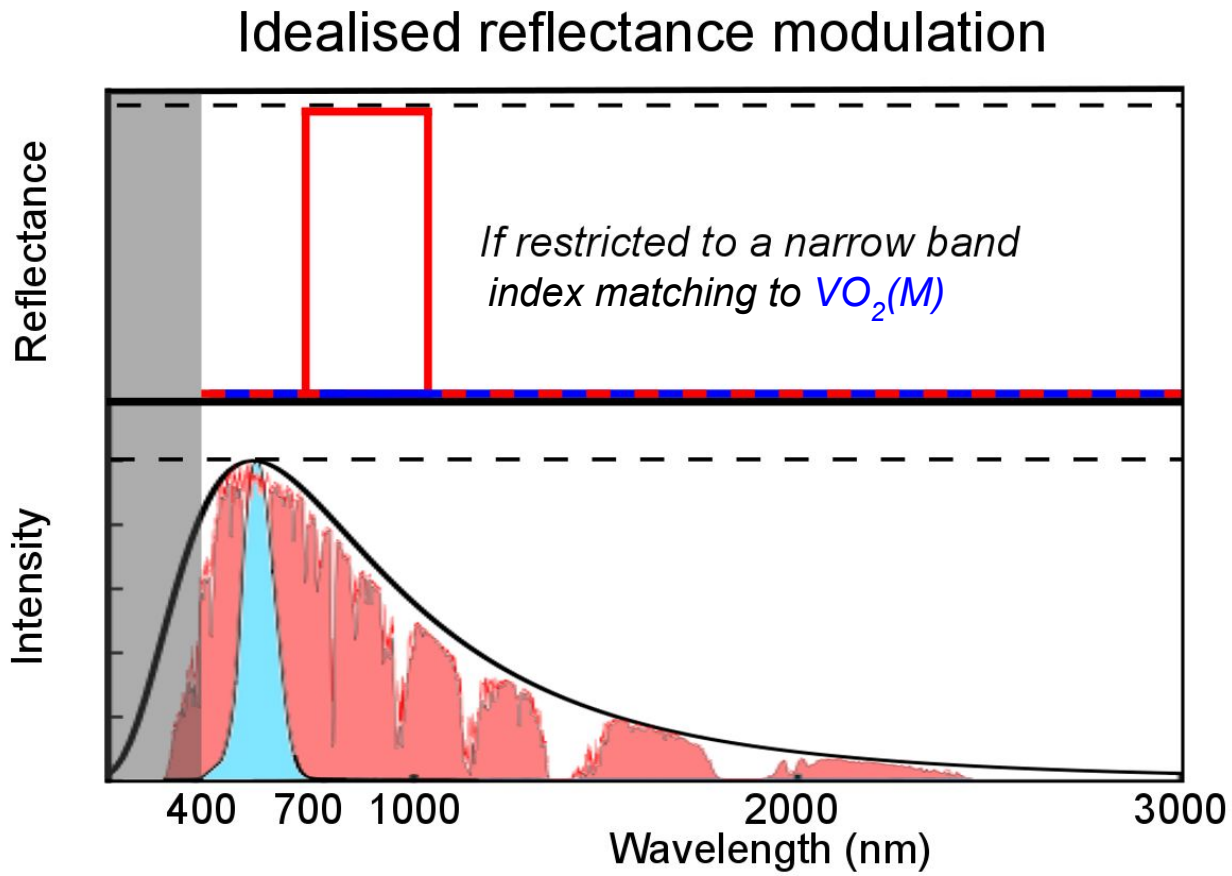


Can be achieved through thin film interference effects

Requires precise control of film thickness

Desired properties:
Minimal visible reflectance in both states (400 - 700 nm)
Large modulation in the NIR where solar intensity is high (700 - 1200 nm)

Practical design considerations



Can be achieved through thin film interference effects

Requires precise control of film thicknesses

Material requirements:

- Transparent in visible region
- Common in window industry
- Scalable fabrication method

Desired properties:
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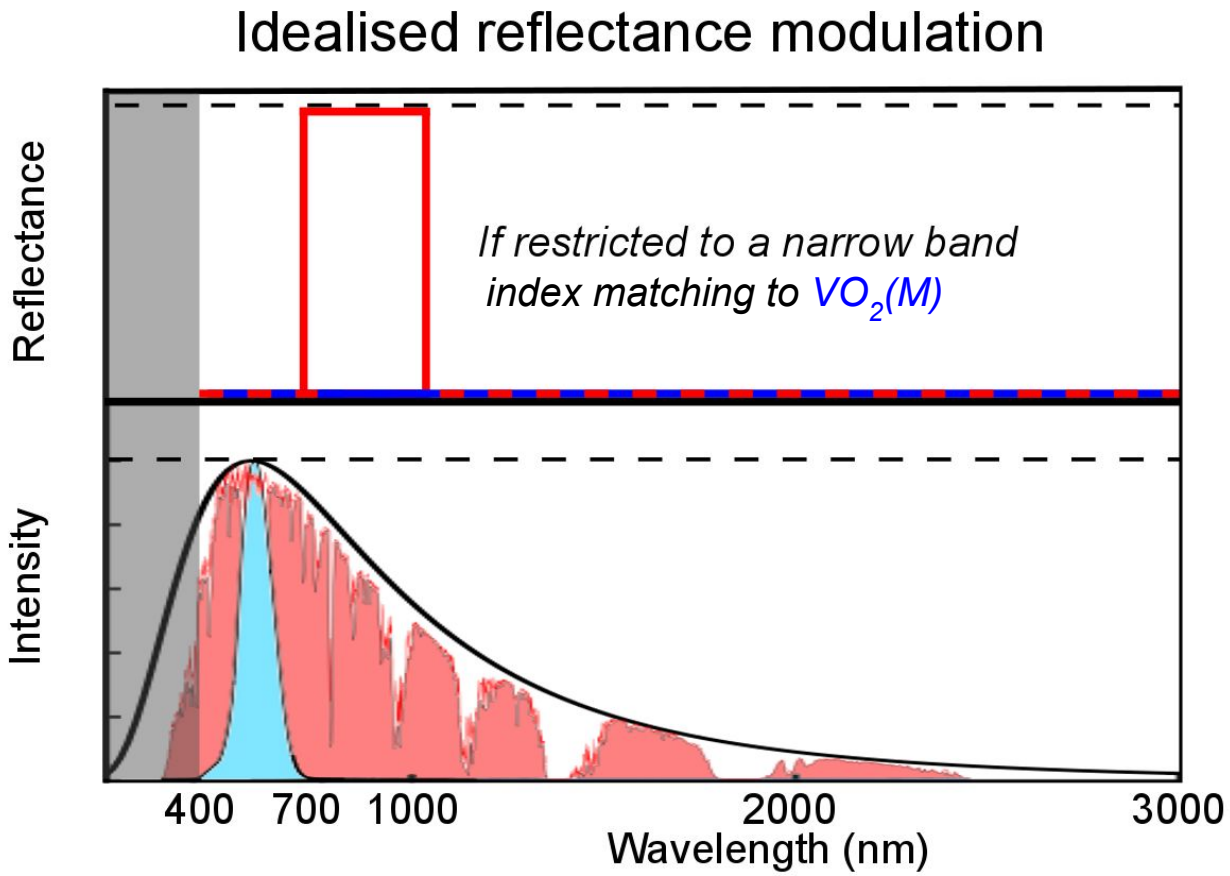
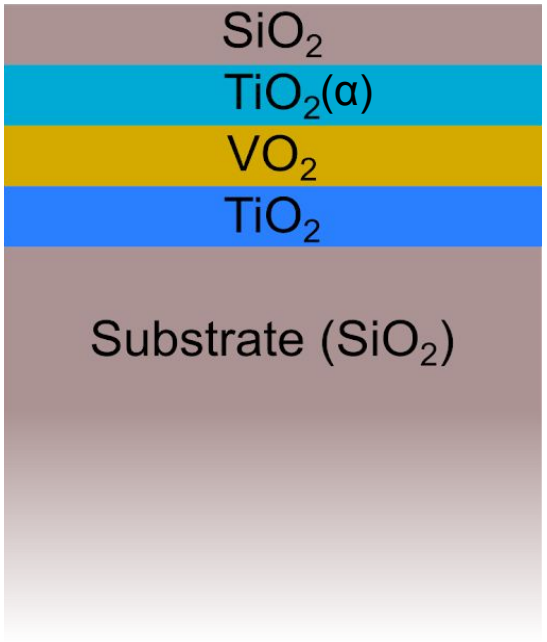
Practical design considerations

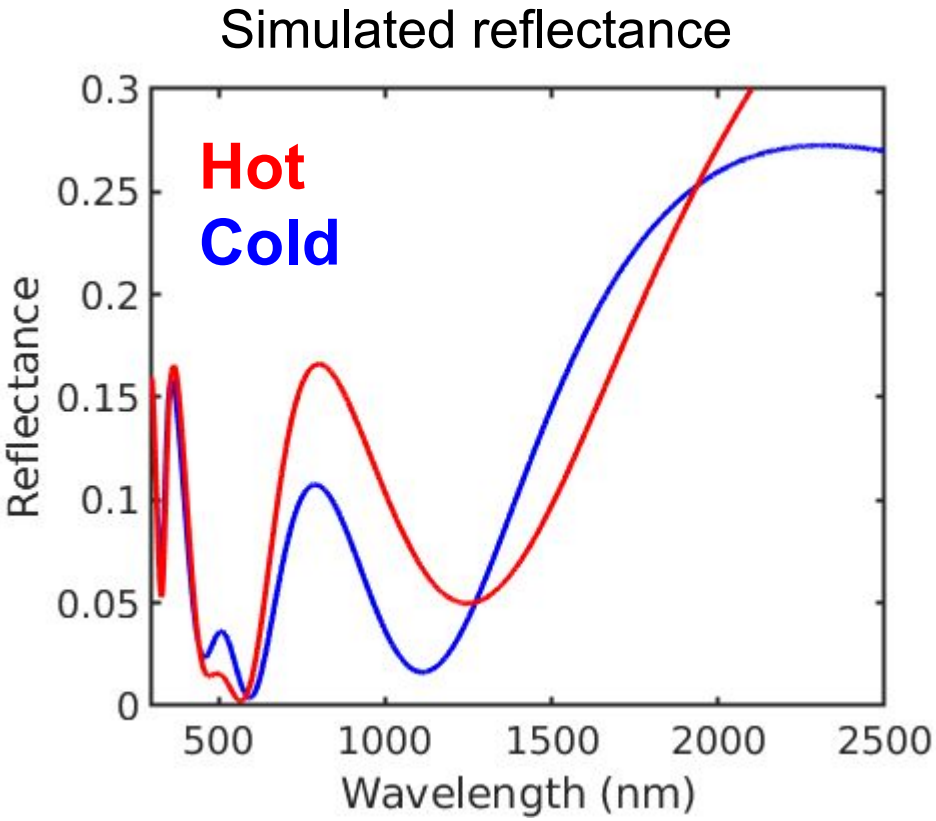


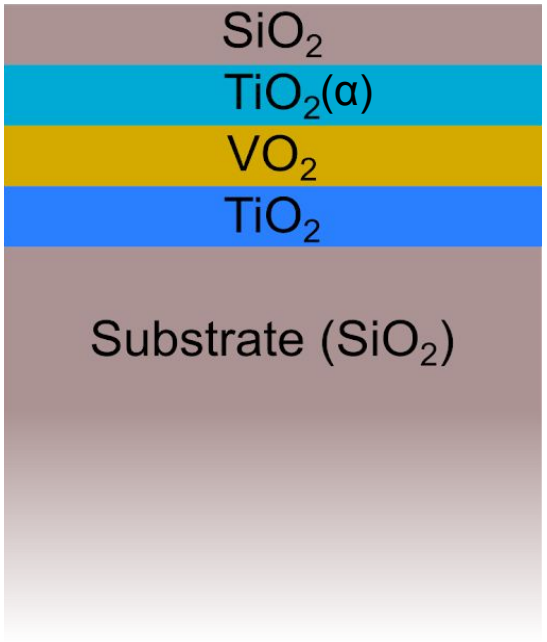


Desired properties:
Minimal visible reflectance in both states (400 - 700 nm)
Large modulation in the NIR where solar intensity is high (700 - 1200 nm)

How well does the design perform?

Practical design considerations





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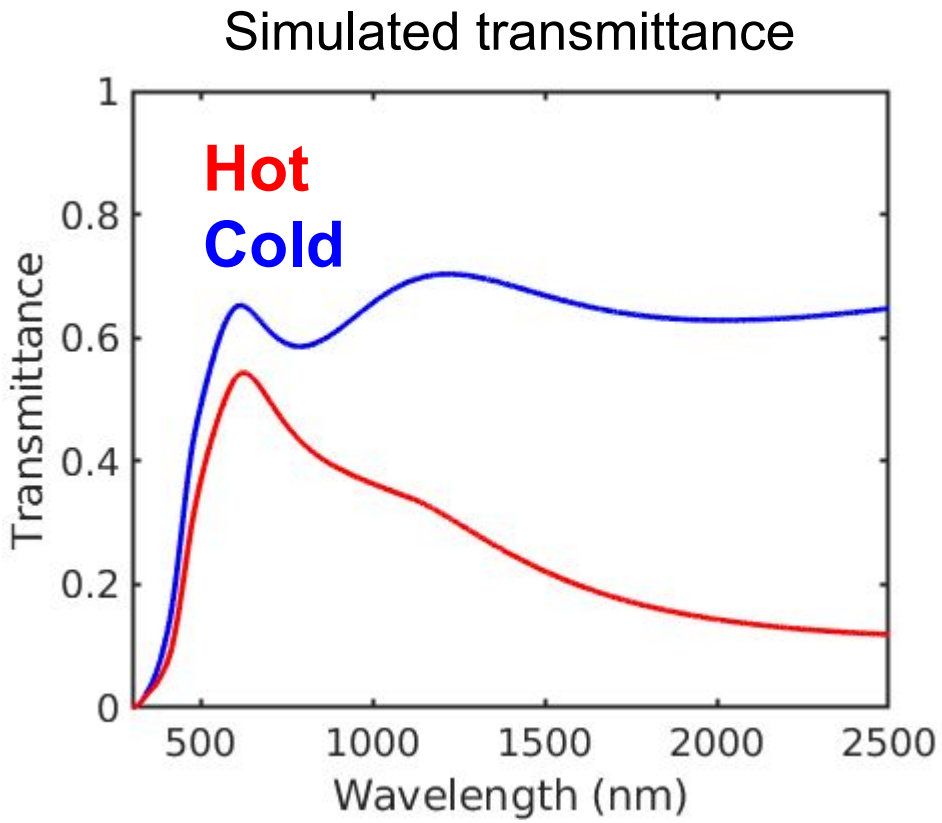

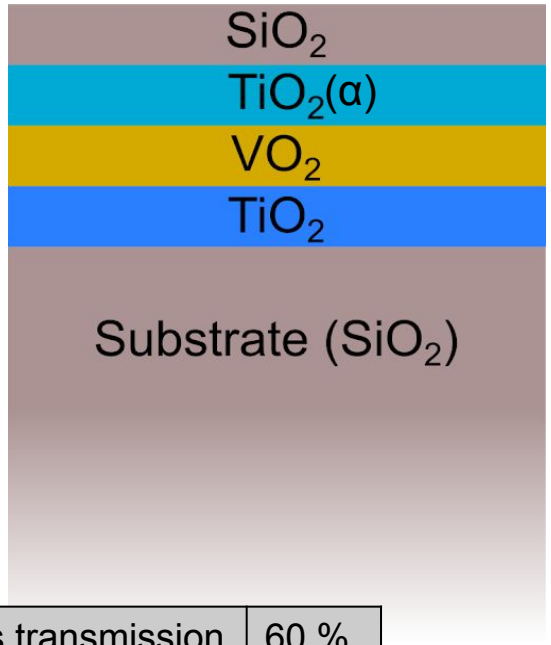

Luminous transmission	60 %
Solar modulation	20 %

Desired properties:
Minimal visible reflectance in both states (400 - 700 nm)
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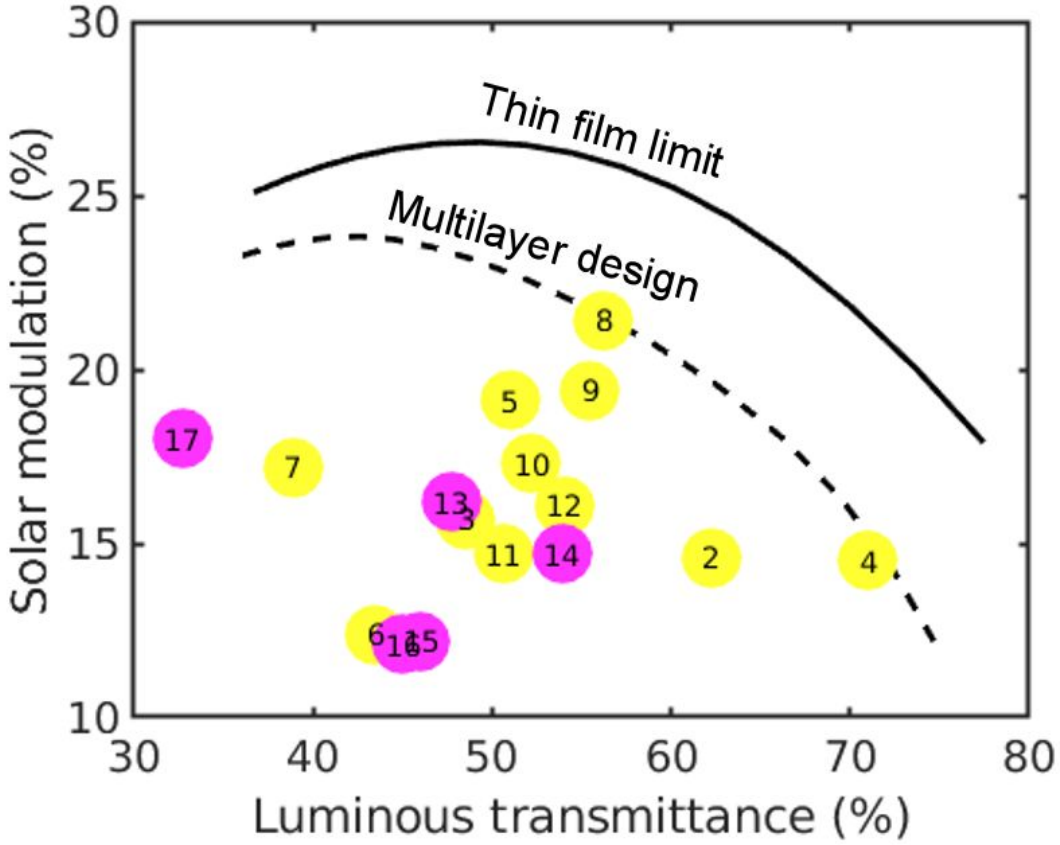
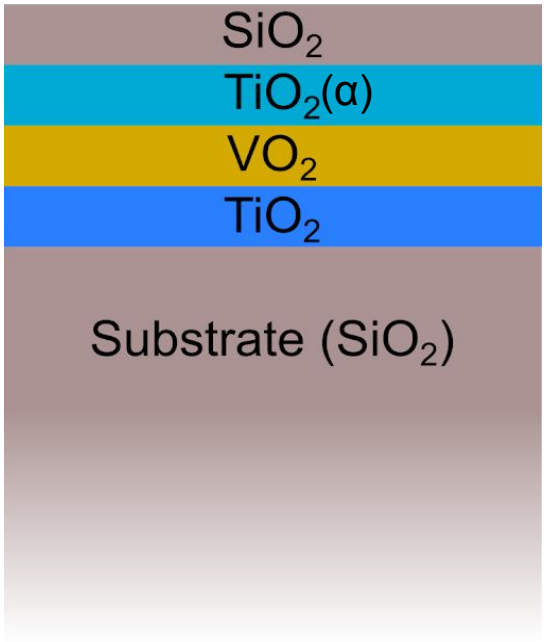
A practical design for high performance





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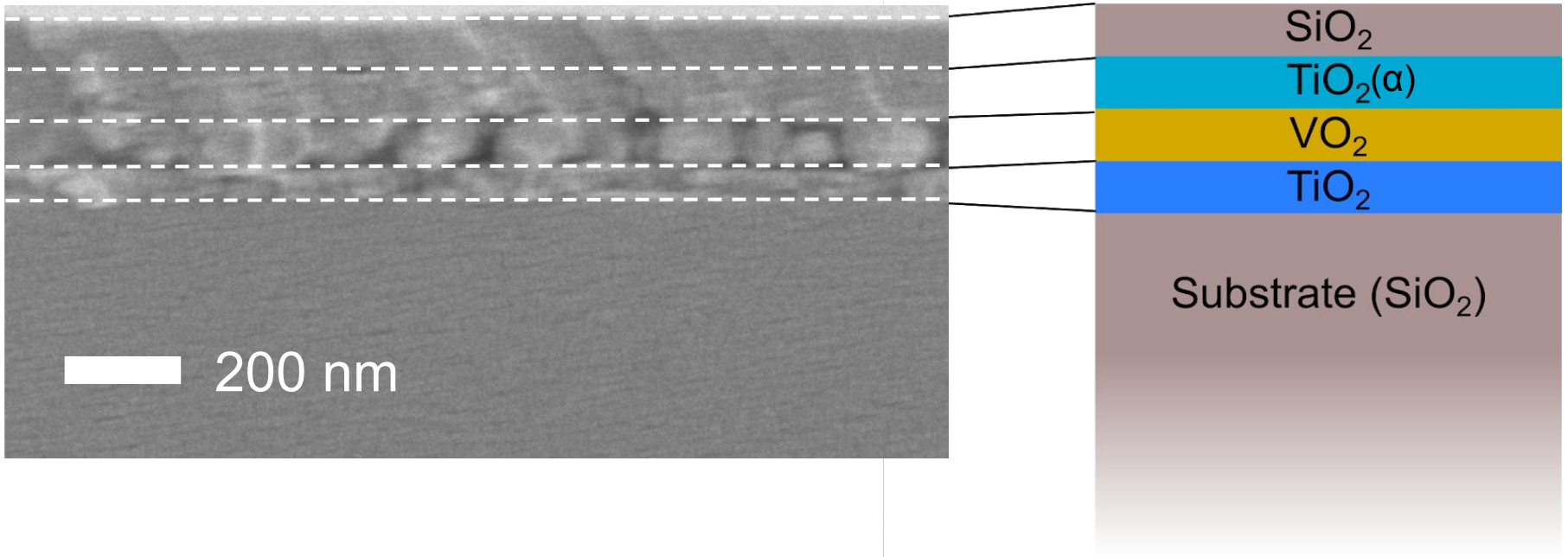
A practical design for high performance

Side-on SEM of fabricated multilayer structure



All layers fabricated using scalable solution based methods

Layer-by-layer breakdown

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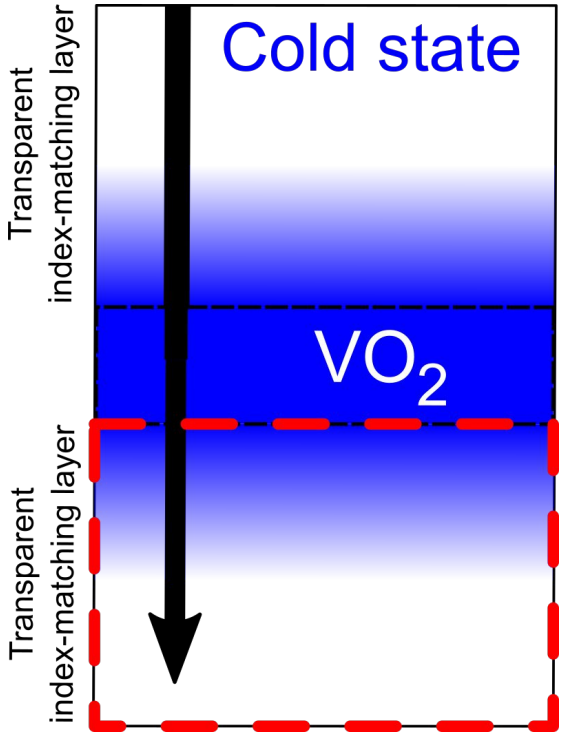
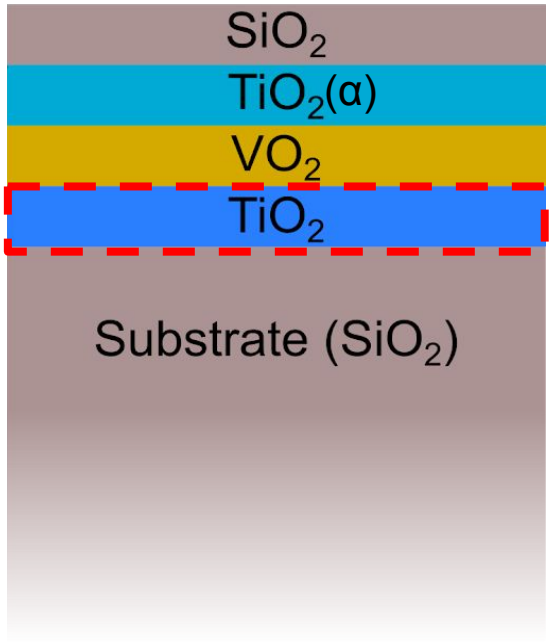
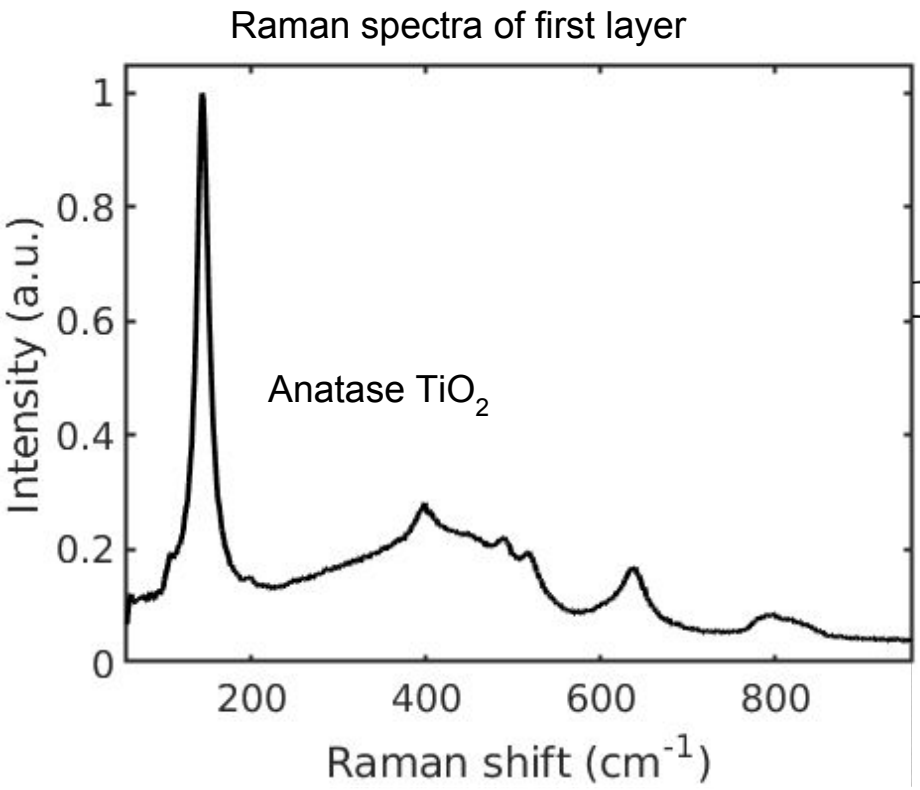
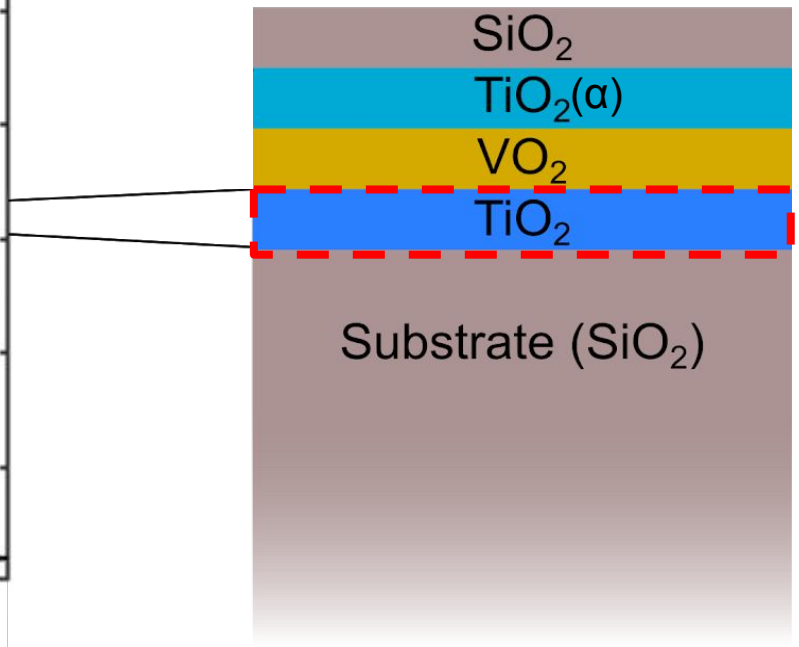




- Index matches between VO_2(M) and SiO_2 substrate

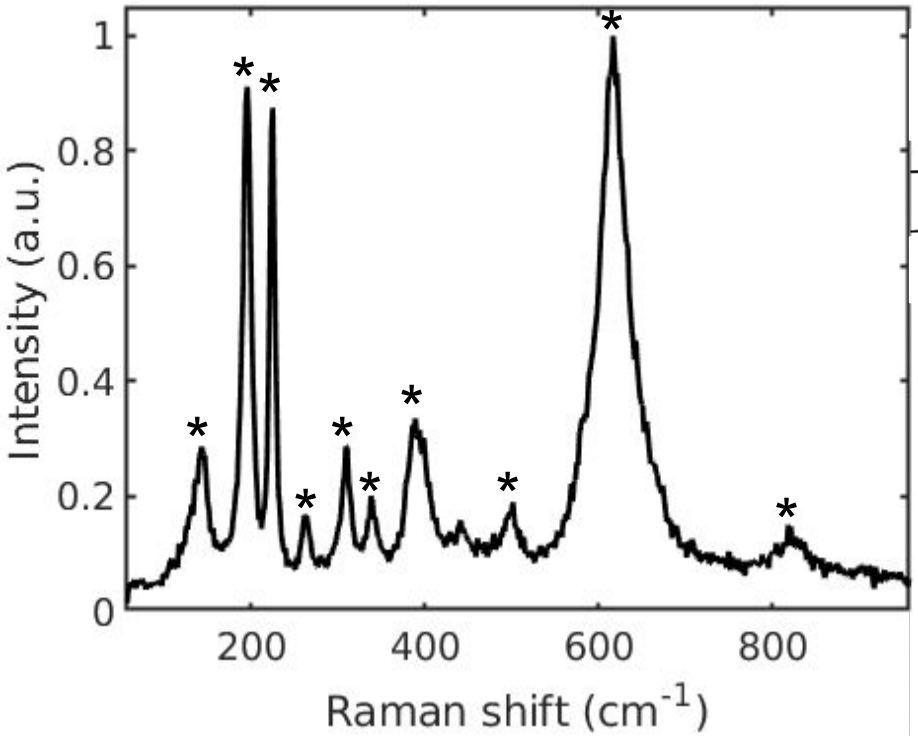
A practical design for high performance

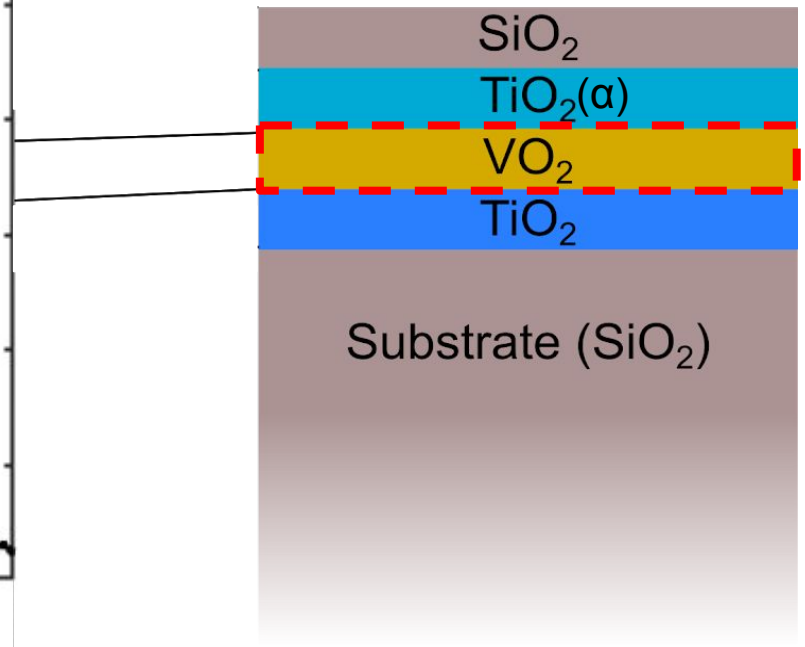




- Index matches between VO_2(M) and SiO_2 substrate
- Anatase TiO_2 serves as a seeding layer for VO_2 growth
- Formed from TTIP sol-gel annealed at 550 °C

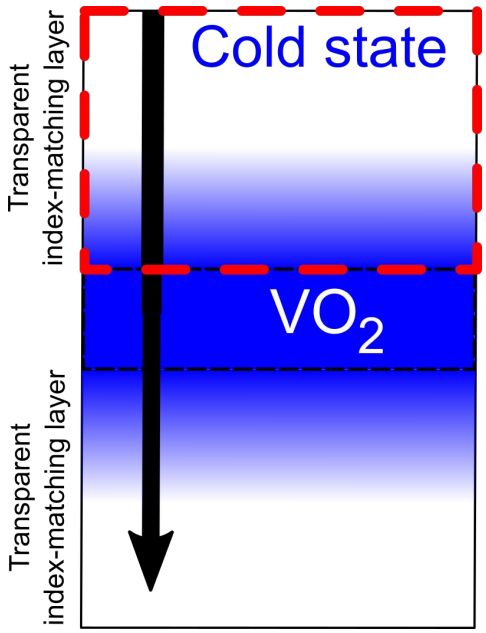
A practical design for high performance

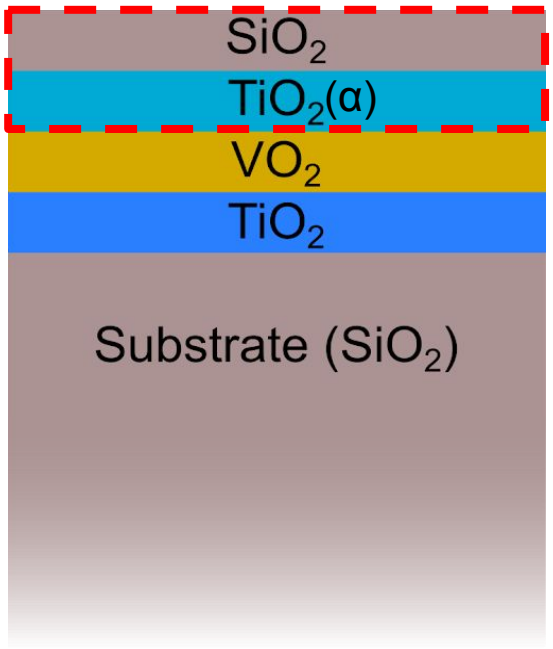




High purity vanadium dioxide formed from vanadium(IV) sol-gel annealed at 550 °C in a low oxygen environment

A practical design for high performance



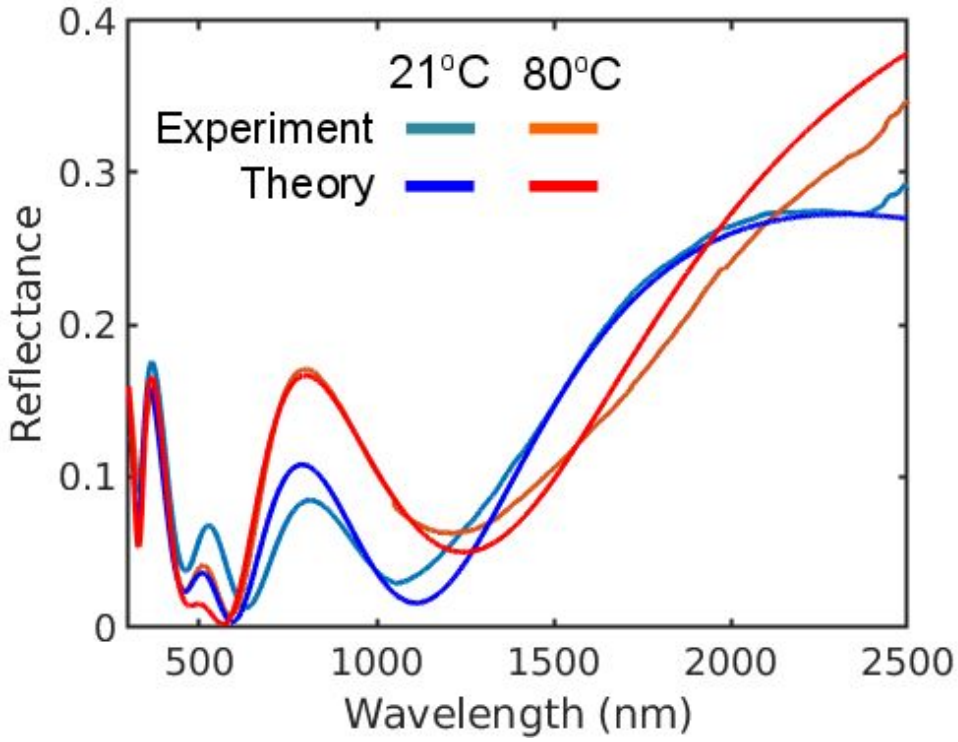


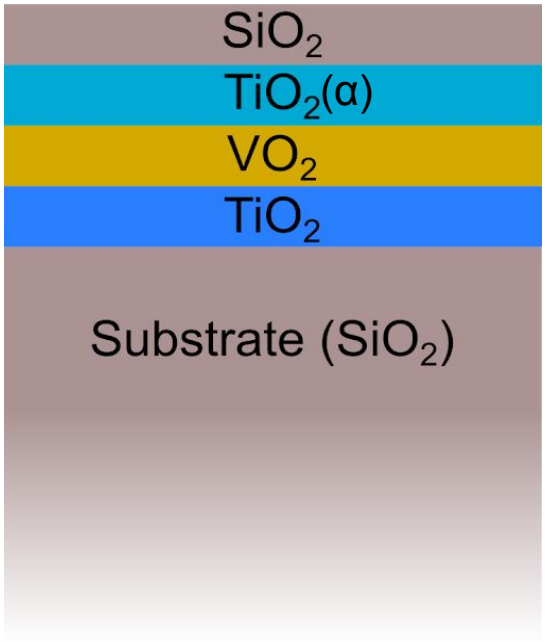
- Two low-temperature amorphous top layers (silica - TEOS ; titania - TTIP) suppress visible reflection and index match between air and VO_2(M)
- Additionally prevents oxidation of VO_2 to V_2O_5

How well does it perform?

A practical design for high performance

Measured reflectance spectra match well with transfer matrix theory





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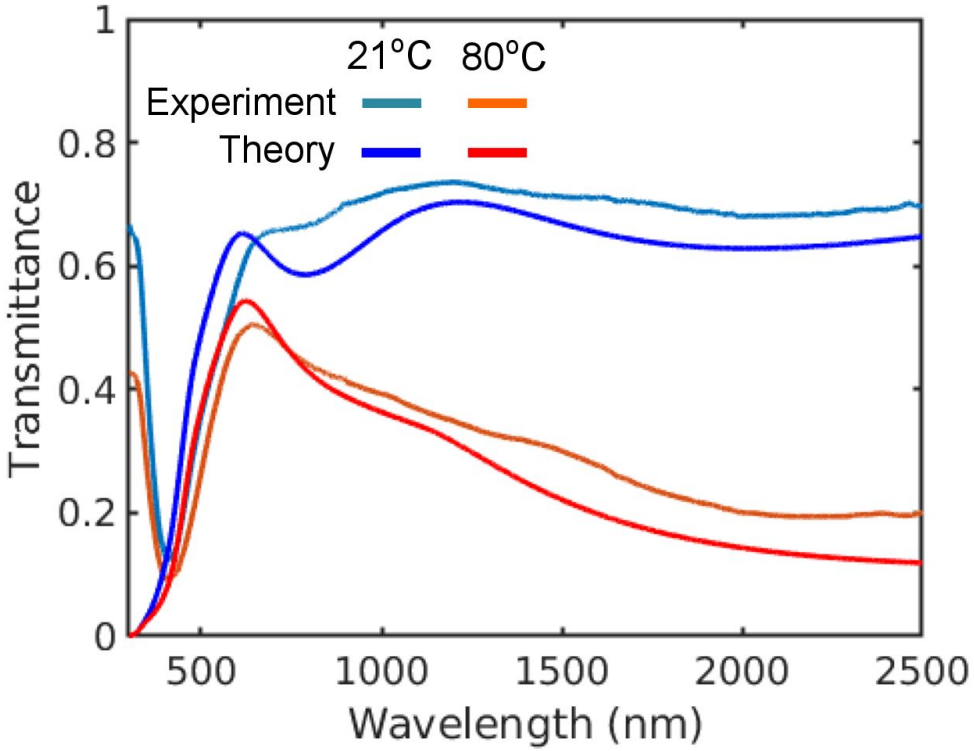
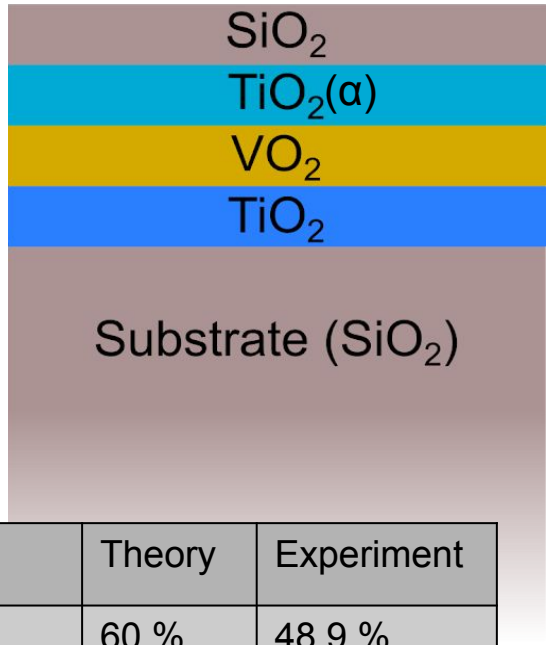
Minimal visible reflectance in both states (400 - 700 nm)
Large modulation in the NIR where solar intensity is high (700 - 1200 nm)

A practical design for high performance

Multilayer fabricated from sol-gel precursors

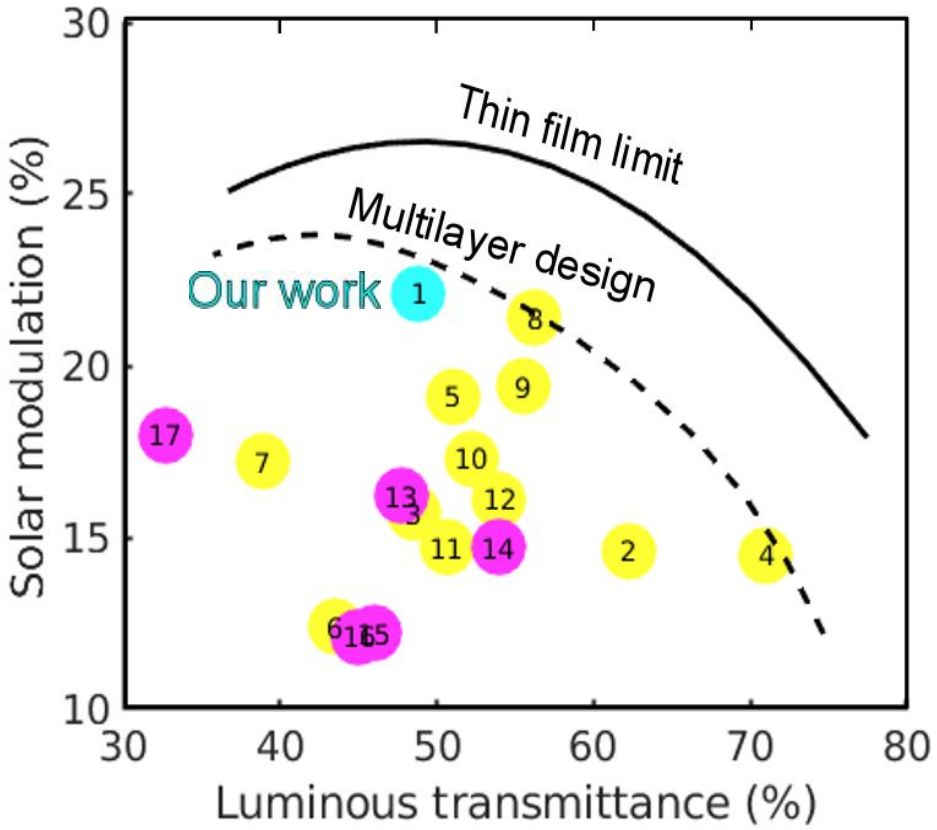




	Theory	Experiment
Luminous transmission	60 %	48.9 %
Solar modulation	20 %	22.1%

Literature context

A practical design for high performance

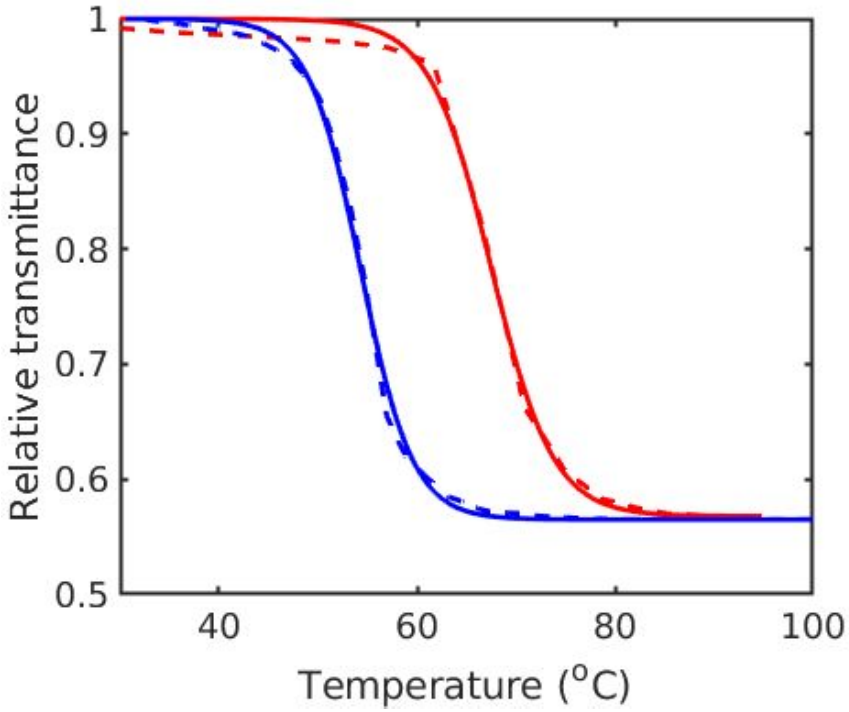


Solar modulation comparable with best nanoparticle coatings and far superior to other thin film coatings

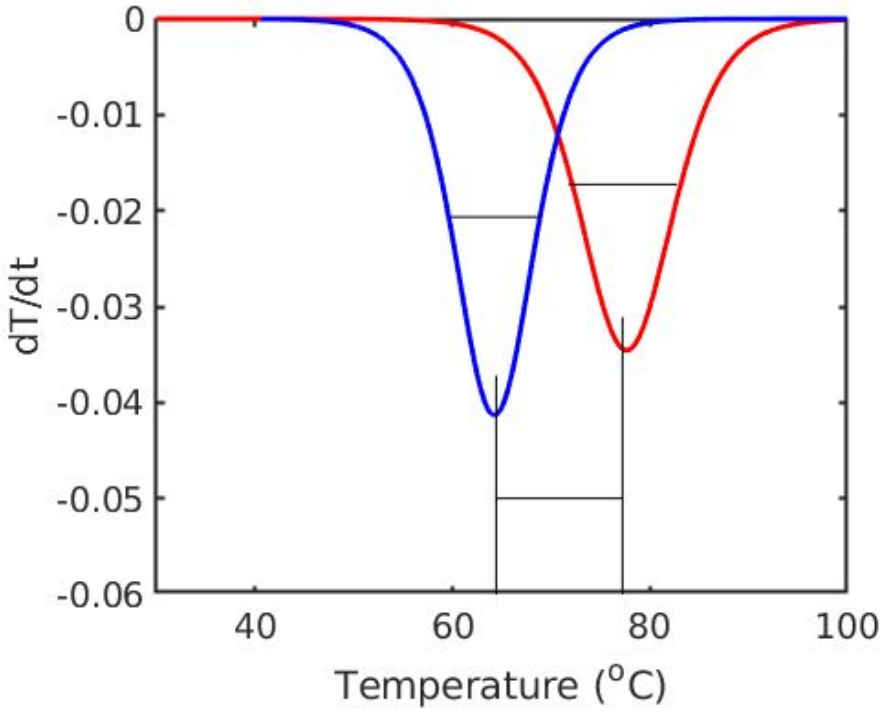
What about hysteresis?

A practical design for high performance

Measured hysteresis loop



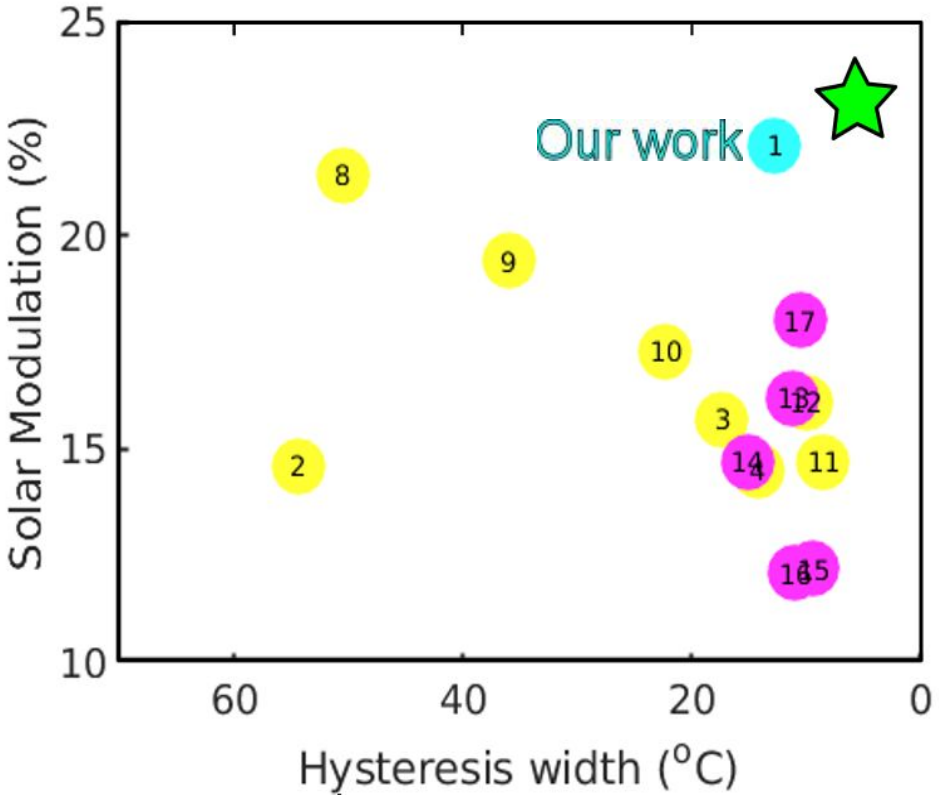
Analysis of first derivative



Hysteresis width	12.8 °C
Gradient width	10.1 °C
Transition temperature	70.8 °C

Literature context

A practical design for high performance



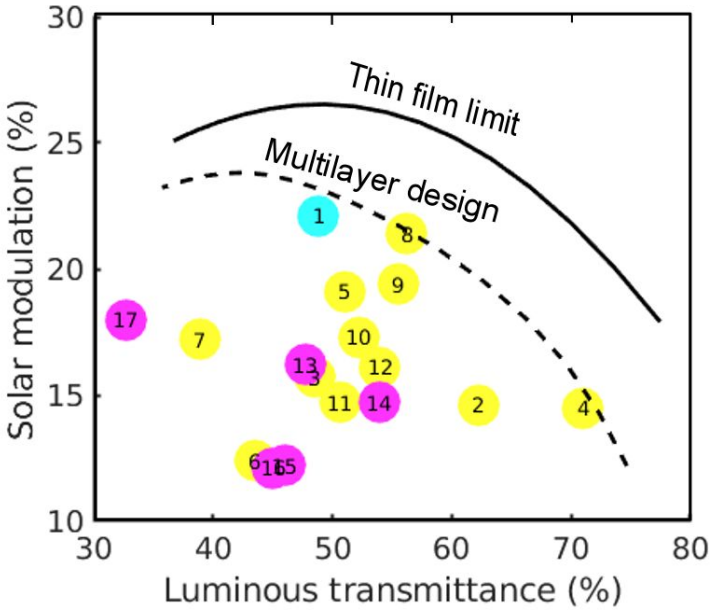
Hysteresis widths very favourable compared to high performing nanoparticle composites

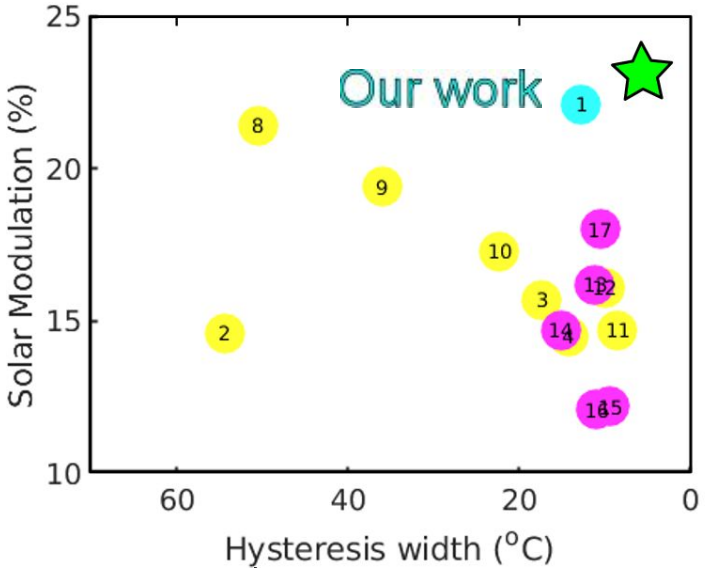
Next steps:

- Tungsten doping to reduce transition temperature to near room temperature
- Evaluate overall energy saving performances using our published method
  - *Scientific Reports* **volume 8**, Article number: 13249 (2018)
- Develop new designs that can get closer to the thin film performance limit

Conclusions:

- There is much room for improvement in thin film vanadium dioxide window coatings
- Design focus should be on improving modulation at wavelengths where solar irradiance is high
- By carefully tailoring thin film interference effects large improvements can be made using common materials





Thanks to ...

Thanks to...

https://www.ee.ucl.ac.uk/pilab

PhD supervisor:
Prof. Ioannis Papakonstantinou

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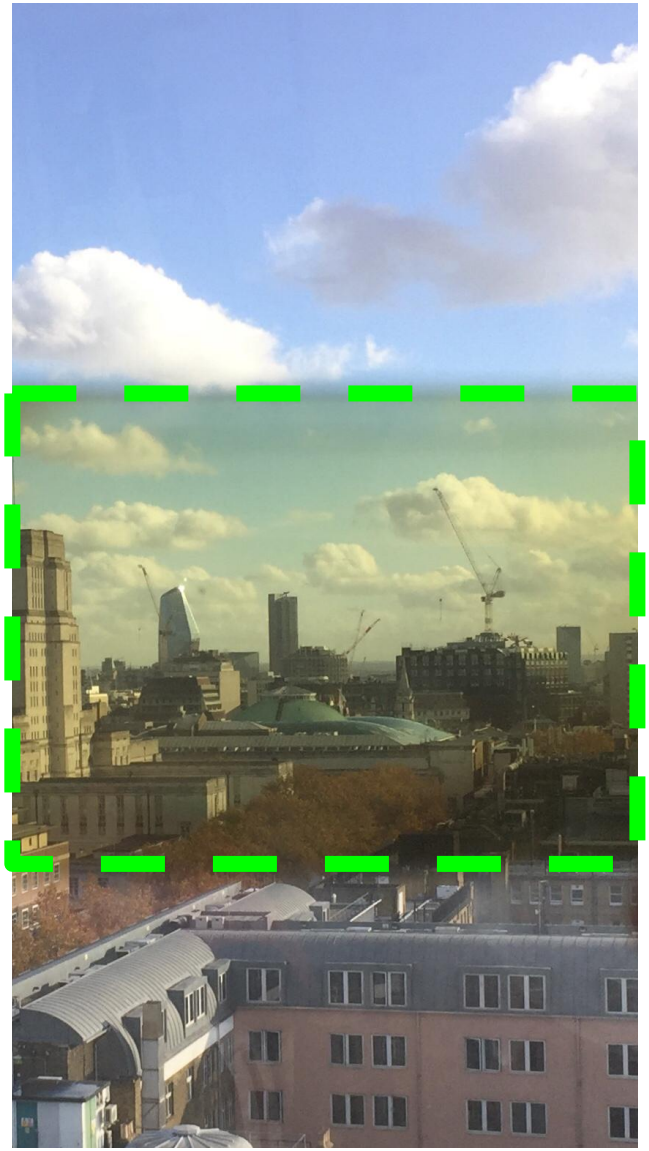
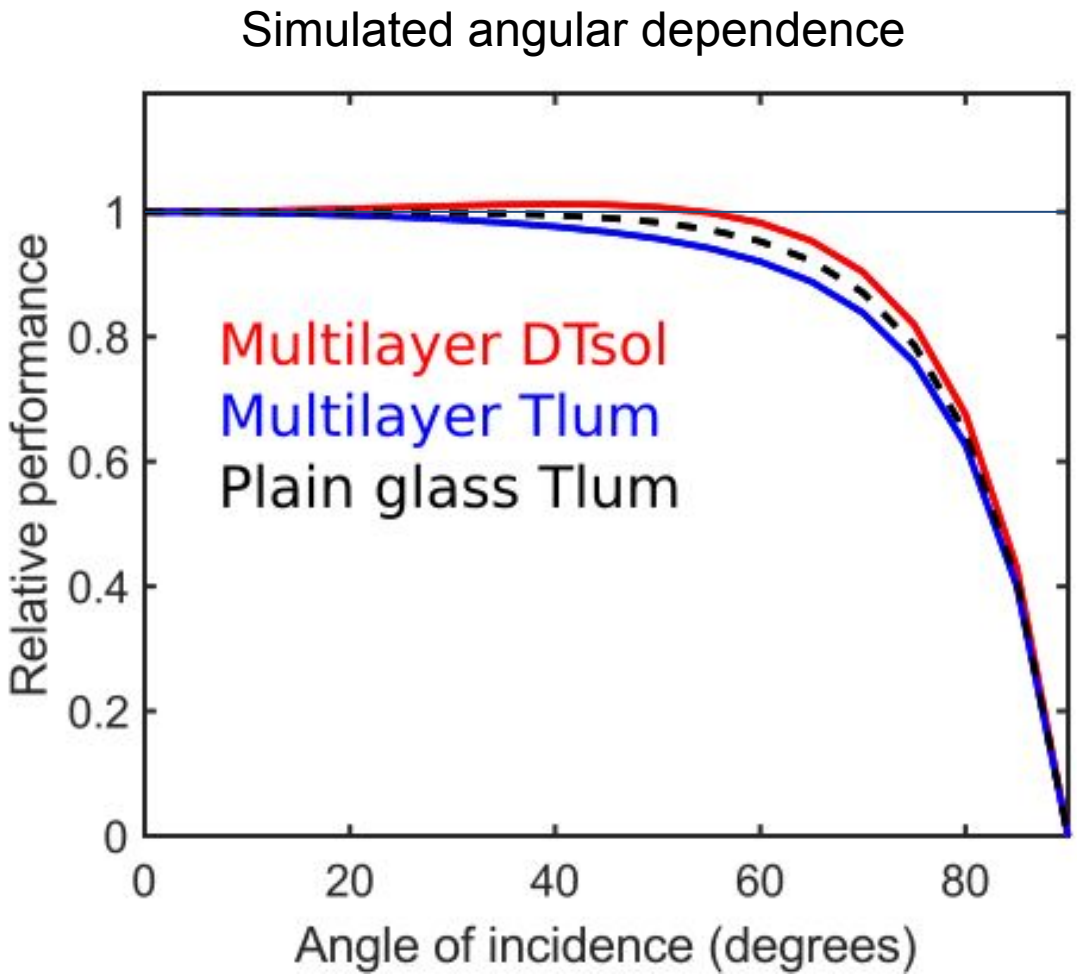
What 60% luminous transmission looks like ...

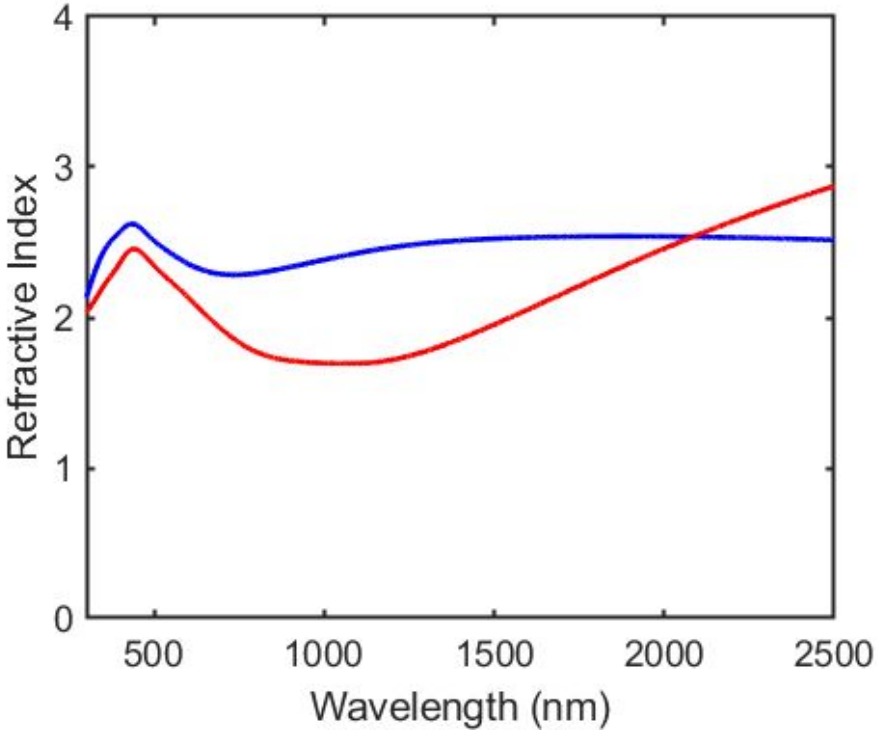


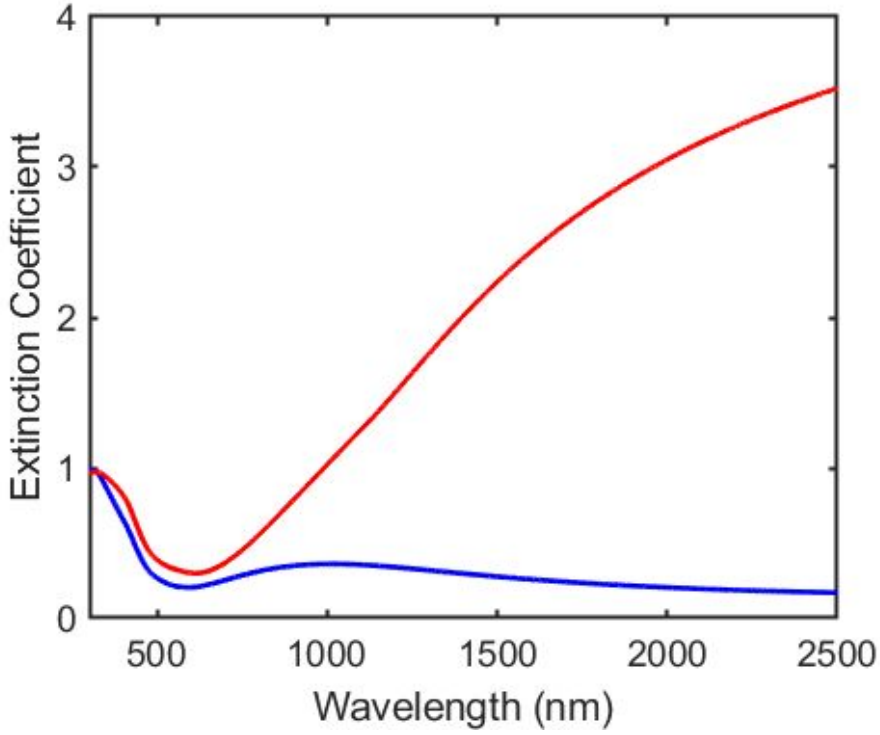
My email address: uk.christian.sol@gmail.com

Angular dependence



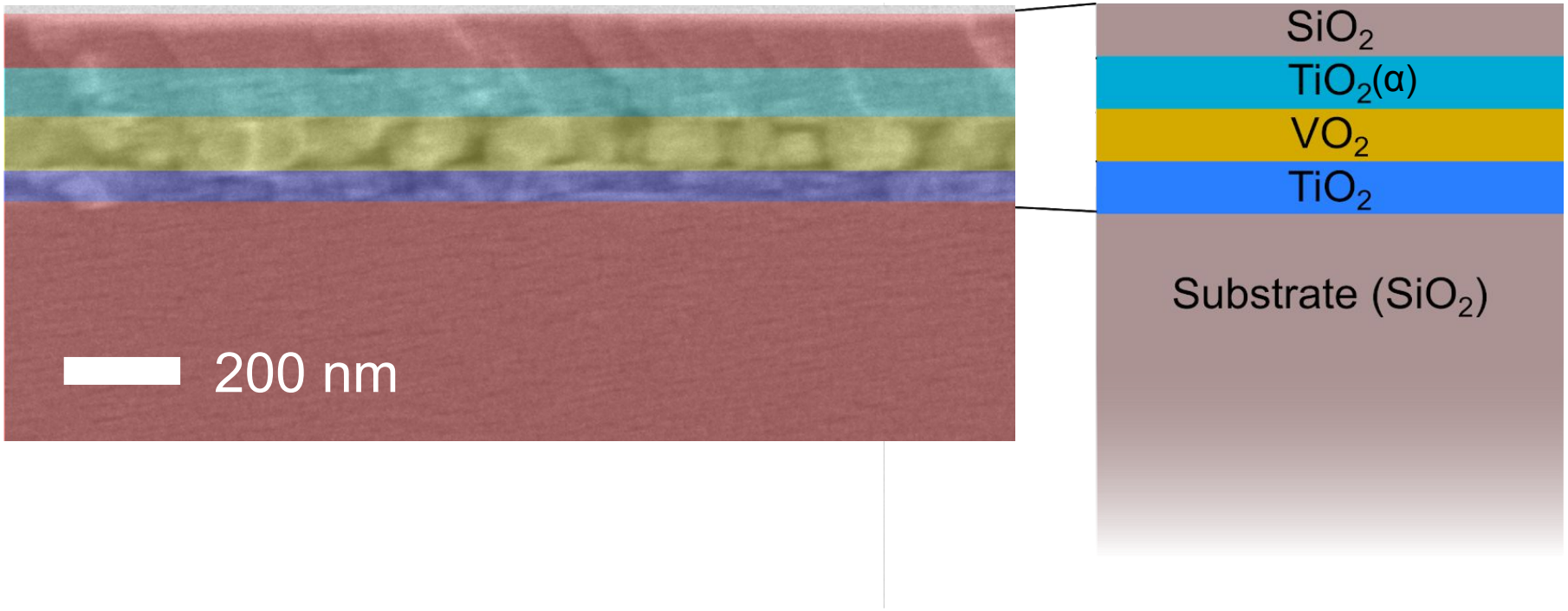
Optical constants





Derived from ellipsometry

A practical design for high performance



- Two low-temperature amorphous top layers (silica - TEOS ; titania - TTIP) suppress visible reflection and index match between air and VO_2(M)
- Additionally prevents oxidation of VO_2 to V_2O_5

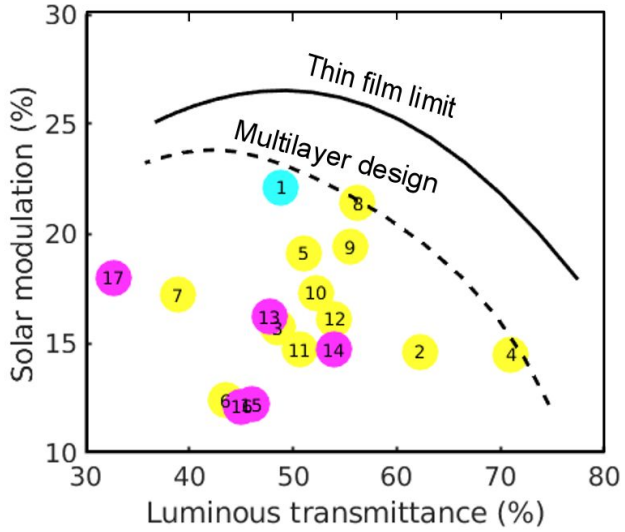
How well does it perform?

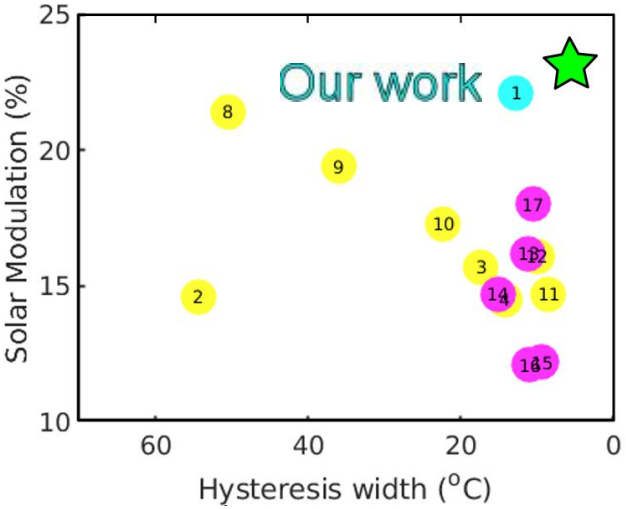
Next steps:

- Tungsten doping to reduce transition temperature to near room temperature
- Evaluate overall energy saving performances using our published method
  - *Scientific Reports* **volume 8**, Article number: 13249 (2018)
- Develop new designs that can get closer to the thin film performance limit

Conclusions:

- There is much room for improvement in thin film vanadium dioxide window coatings
- Design focus should be on improving modulation at wavelengths where solar irradiance is high
- By carefully tailoring thin film interference effects large improvements can be made using common materials





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