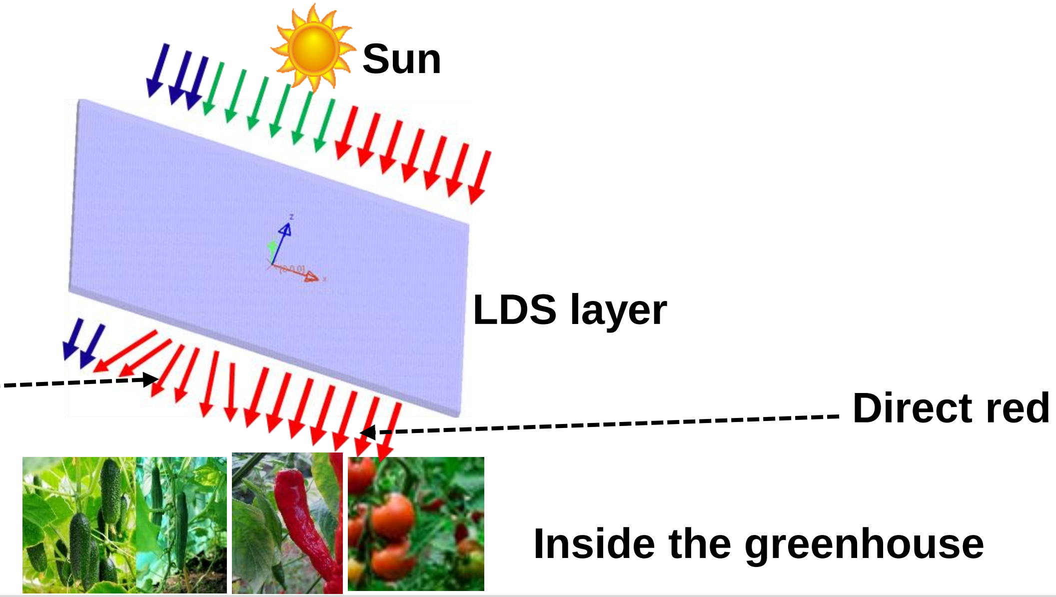
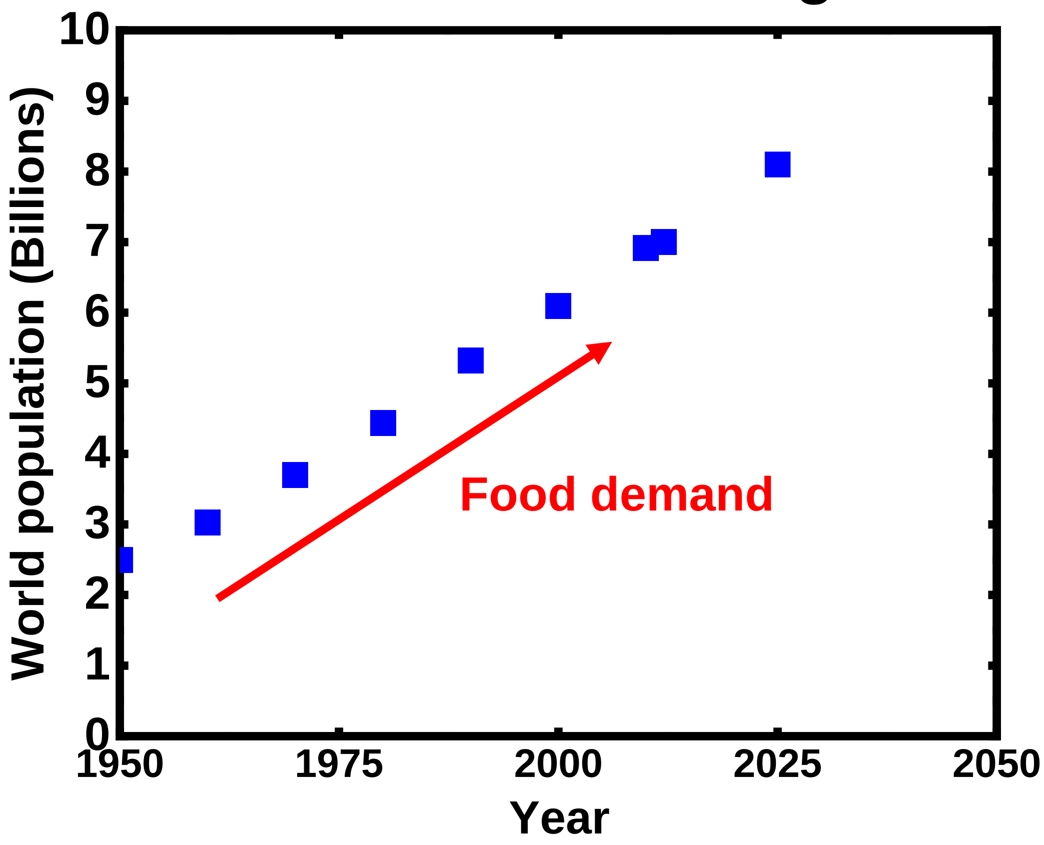
Micro-Structured Luminescent Downshifting Layers for Improved Photon Extraction in Smart Greenhouses

JUVET FRU,[1] DMITRY BUSKO,[1] AND BRYCE RICHARDS[1,2]

[1]*Institute of Microstructure Technology, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344, Eggenstein-Leopoldshafen, Germany*
[2]*Light Technology Institute, Karlsruhe Institute of Technology, Engesserstrasse 1, 376131, Karlsruhe, Germany*

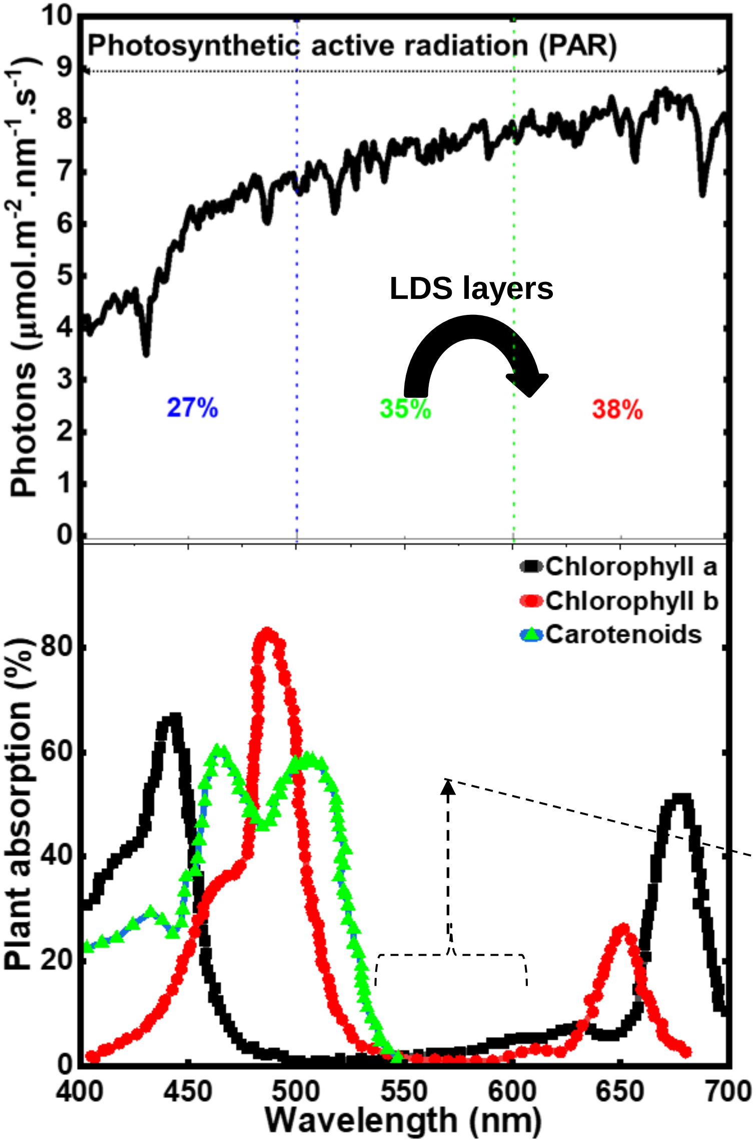


Introduction-challenges



- Rising global population is driving unprecedented growth in food demand
- Urgent need for efficient agricultural technologies to meet rising food demand
- Greenhouses allow crop yield control but often underutilize the solar spectrum

Luminescent downshifting (LDS) greenhouses



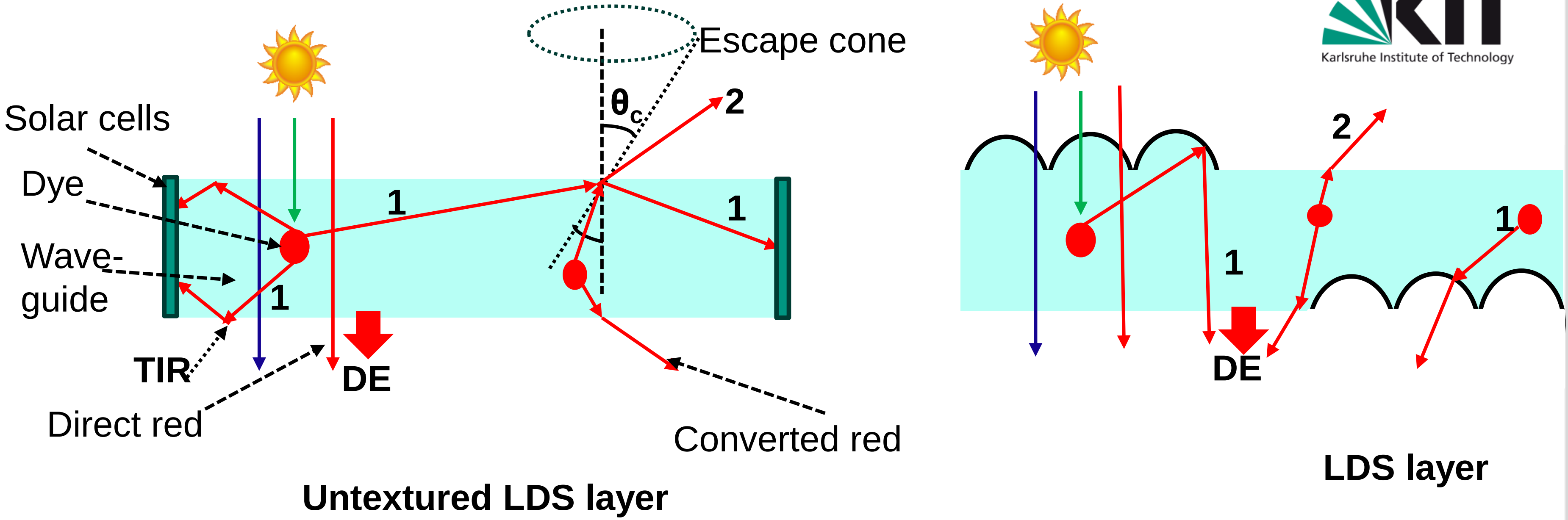
- LDS greenhouses boost PAR use by actively managing the solar spectrum
- Spectral management turns underutilized green light into red and harmful UV into blue (Burak et al.) or red (Müller et al.)
- Converted photons are directed into the greenhouse, boosting photosynthesis and crop yield

Weak green absorption is reason for green color

Müller, R., Okokhere-Edeghoghon, B., Janowicz, N.J., Bond, A.D., Kociok-Kohn, G., Cox, L.M.R., Garzon, D., Waine, T.W., Truckell, I.G., Gage, E. and Thompson, A.J., 2025. Transparent, sprayable plastic films for luminescent down-shifted-assisted plant growth. *Advanced Materials Technologies*, *10*(6), p.2400977

Burak, H., Dunbar, A. and Gilmour, D.J., 2019. Enhancement of Dunaliella salina growth by using wavelength shifting dyes. *Journal of Applied Phycology*, *31*(5), pp.2791-2796

Spectral conversion layers for greenhouses



- Untextured LDS layer: spectral conversion and edge-directed luminescence; escape cone loss = 13% for ideal system
- LDS layers: spectral conversion and enhanced downward extraction (DE) of converted photons ; escape cone loss (DE) > 13%
- Enhancement of DE efficiency depends on bulk scattering or surface texturing
- Texturing boosts DE by increasing the critical angle, enlarging the escape cone

(Shen et al. and Xu et al.)

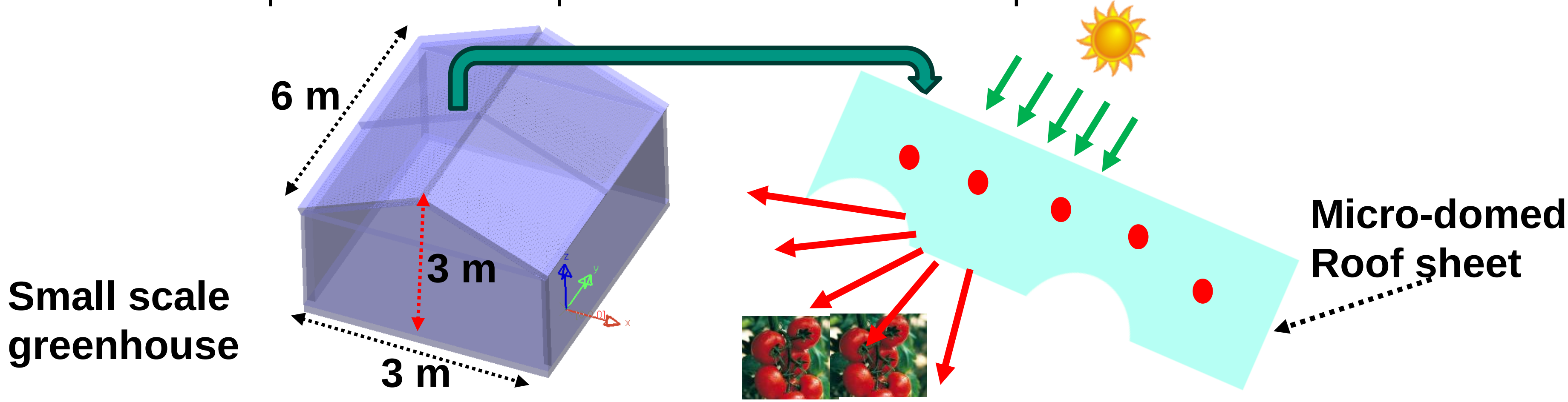
1. L. Shen, R. Lou, A. Aili, C. J. Huggins, and X. Yin, "Microstructure Engineered Photon-Managing Films for Solar Energy to Biomass Conversion," Adv. Energy Mater. **13**, 2204393 (2023).

2. Z. Xu, M. Portnoi, and I. Papakonstantinou, "Micro-cone arrays enhance outcoupling efficiency in horticulture luminescent solar concentrators," Opt. Lett. **48**, 183 (2023).

Previous studies and motivation for this work

Authors	Area	Thickness	Shape and pisition of micro-strcutures	Dimensions of micro-structure	Performance
Shen et al. (2023)	1 cm^2	210 µm	Micro-domes on top surface	Diameter = 400 µm, Height = 65 µm	DE = 65%
Xu et al. (2023)	64 cm^2	5 mm	Inverted micro-cones on bottom surface	Diameter = 100 µm Height = 60 µm (aspect ratio = 1.2)	DE = 39%

- Top-surface micro-structures are prone to dust, organic matter, and abrasion
- Micro-domes perform well on top surfaces but remains unexplored at bottom surface



L. Shen, R. Lou, A. Aili, C. J. Huggins, and X. Yin, "Microstructure Engineered Photon-Managing Films for Solar Energy to Biomass Conversion," Adv. Energy Mater. **13**, 2204393 (2023).

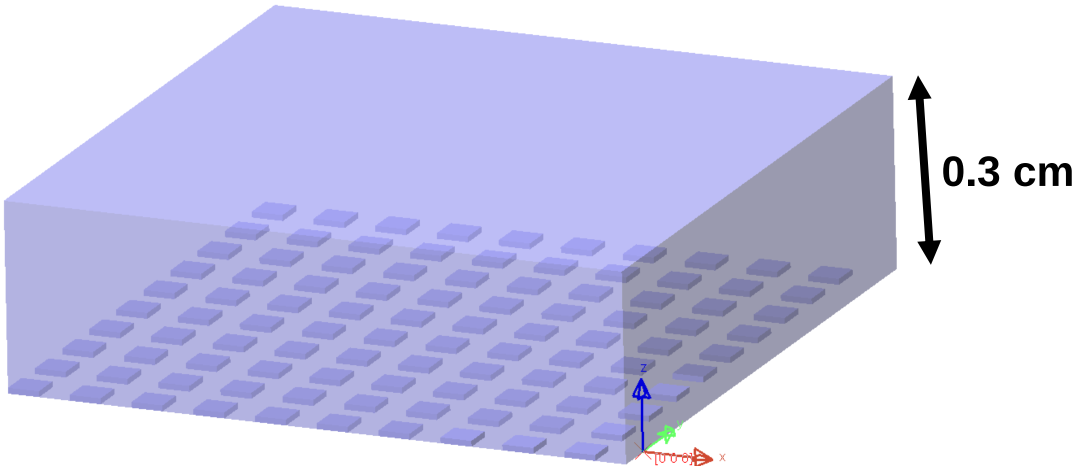
Z. Xu, M. Portnoi, and I. Papakonstantinou, "Micro-cone arrays enhance outcoupling efficiency in horticulture luminescent solar concentrators," Opt. Lett. **48**, 183 (2023).

Objectives

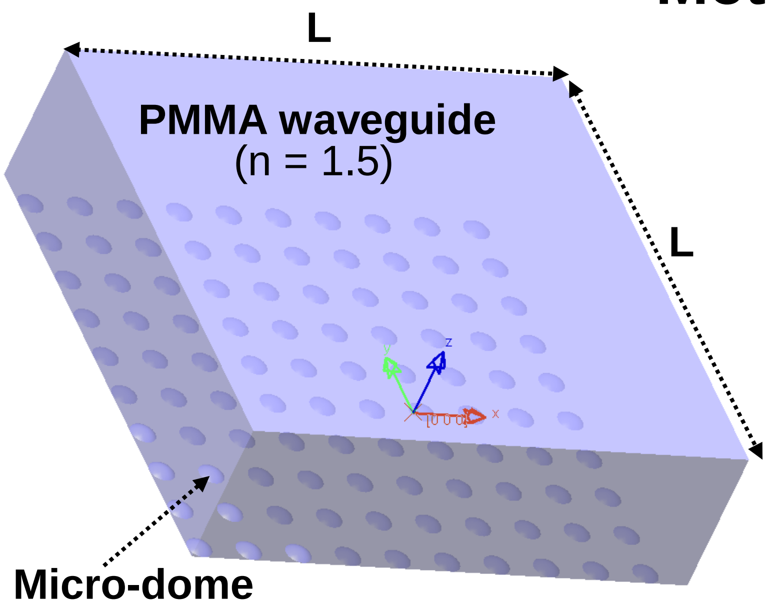
- Compare DE efficiency of thick textured LDS layer with inward-facing bottom microdomes to that of a planar LDS layer of identical dimensions

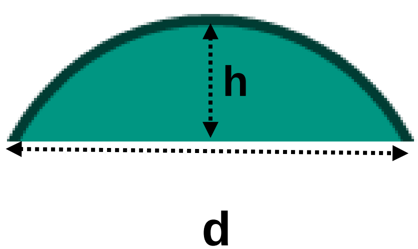
- Show that upscaling thicker textured LDS layers enhances DE efficiency

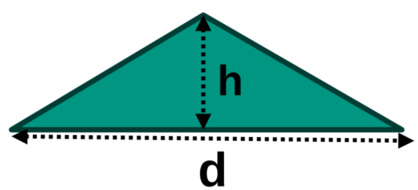
- Demonstrate that micro-cuboids extract photons more effectively than domes, pyramids, or cones in thick textured LDS layer

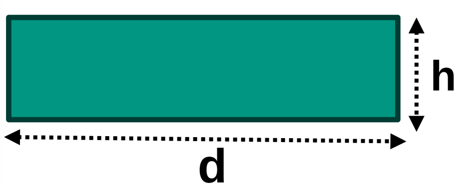


Method - Ray tracing



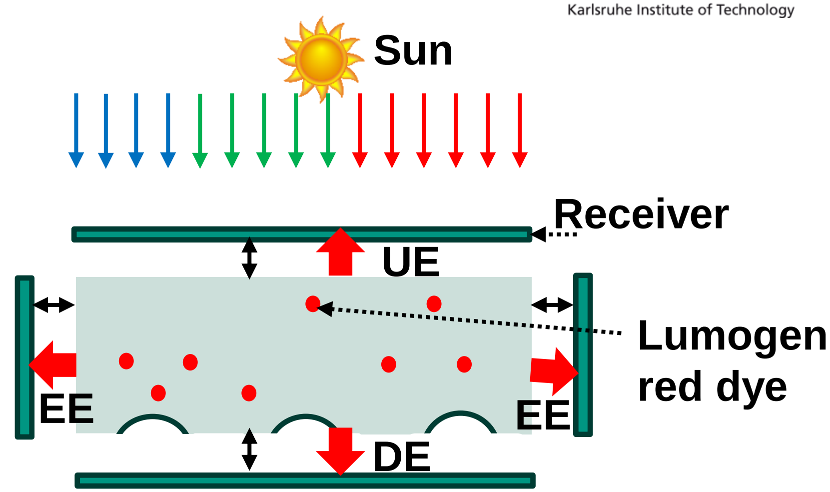


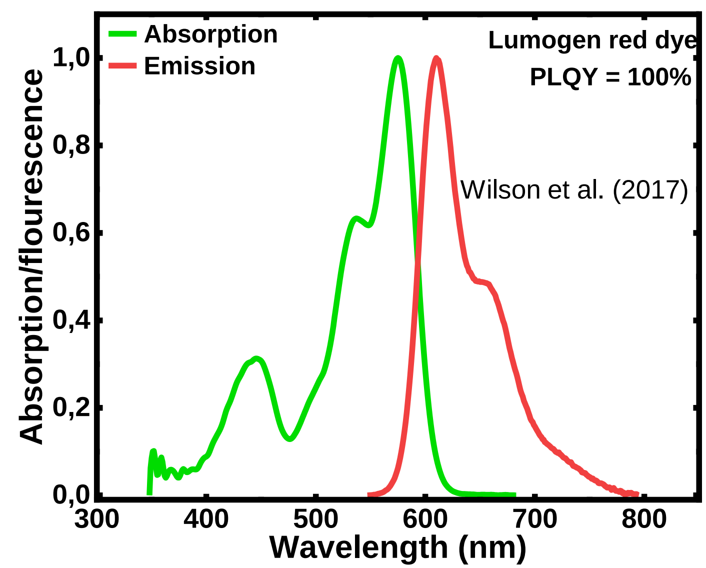




- Except stated otherwise, h = 90 µm, d = 500 µm

❖ Drawings were done in Solidworks

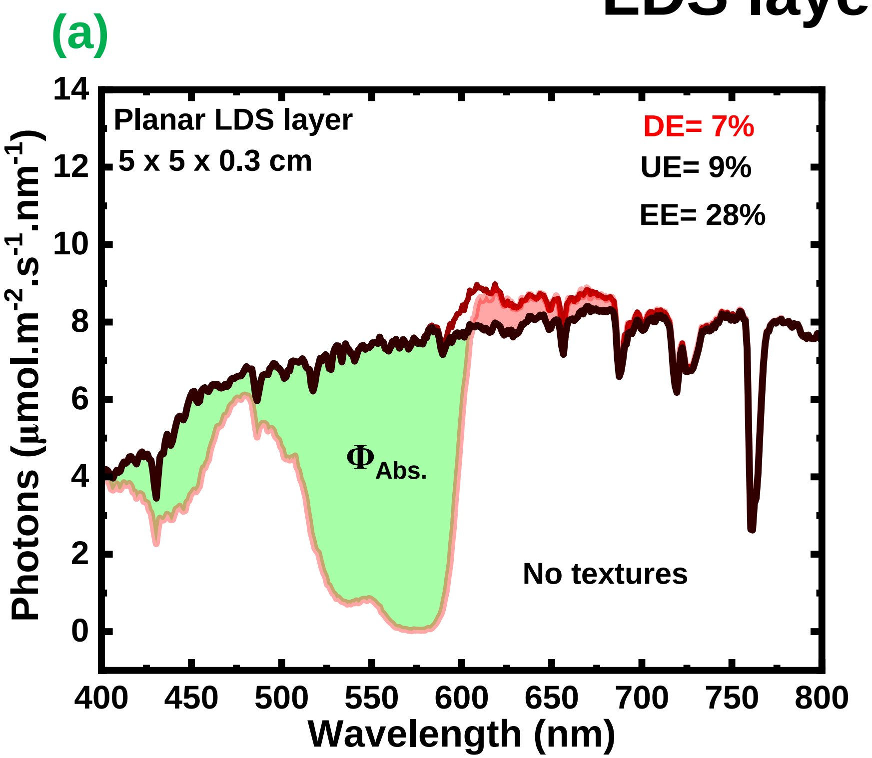


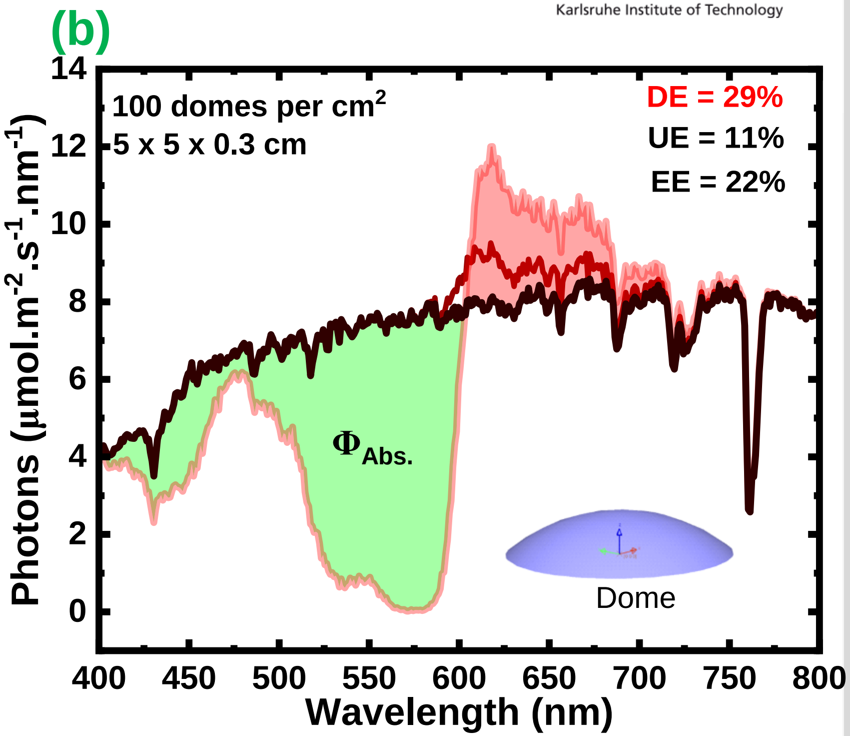


❖ Monte carlo Ray tracing (size) ≫ λ

L. R. Wilson, E. Klampaftis, and B. S. Richards, "Enhancement of Power Output from a Large-Area Luminescent Solar Concentrator with 4.8× Concentration via Solar Cell Current Matching," IEEE J. Photovoltaics **7**, 802–809 (2017).

Results - Extraction efficiency of planar and textured LDS layers



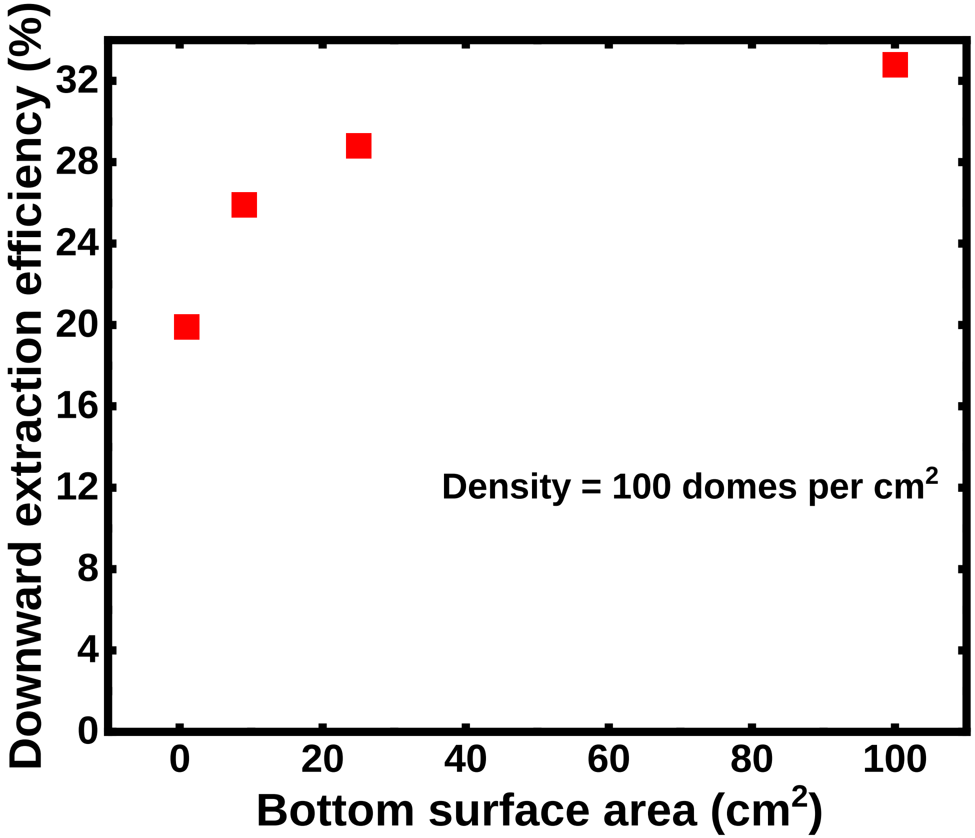


Simulated spectral irradiance for planar LDS layers—(a) untextured with smooth edges and (b) textured with indented microdomes at bottom arranged in a rectangular close pattern

- DE for planar LDS layer is less than theoretical value of 13% because of reabsorption by dye
- Embedding inverted micro-domes (100 domes cm^2) boosts DE over 4×
- The micro-domes broaden the escape cone at the lower surface, enhancing DE

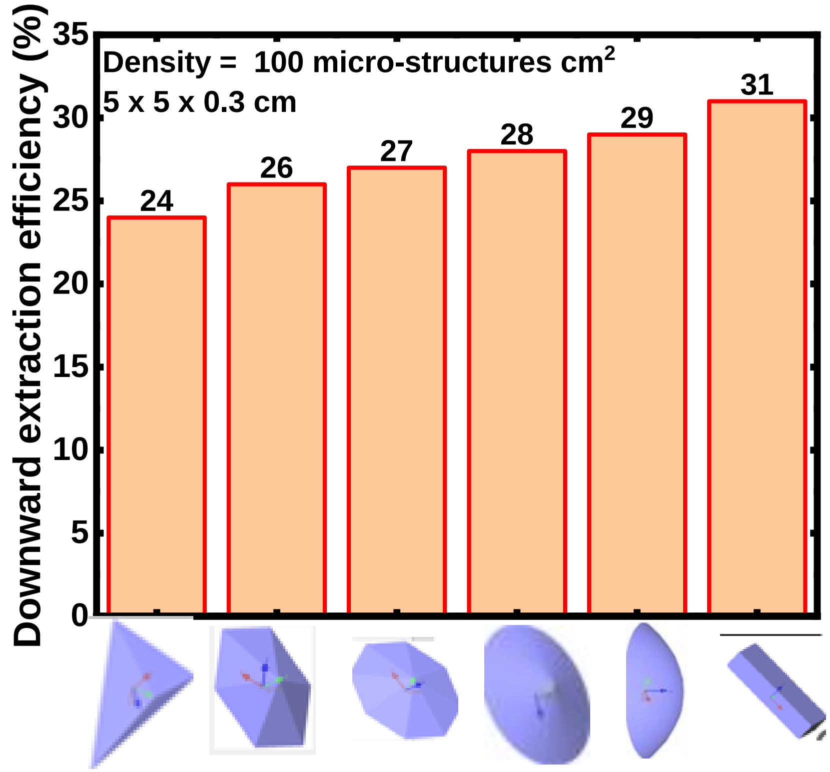
Xu, Z., Yu, Y. and Papakonstantinou, I., 2025. Performance Metrics and Loss Mechanisms in Horticulture Luminescent Solar Concentrators. *IEEE Journal of Selected Topics in Quantum Electronics*

DE efficiencies vs. bottom surface area



- DE efficiency increases with area, approaching a limit equal to EE + DE
- This is good news for upscaling
- Increase is due to reduced edge effects with larger area

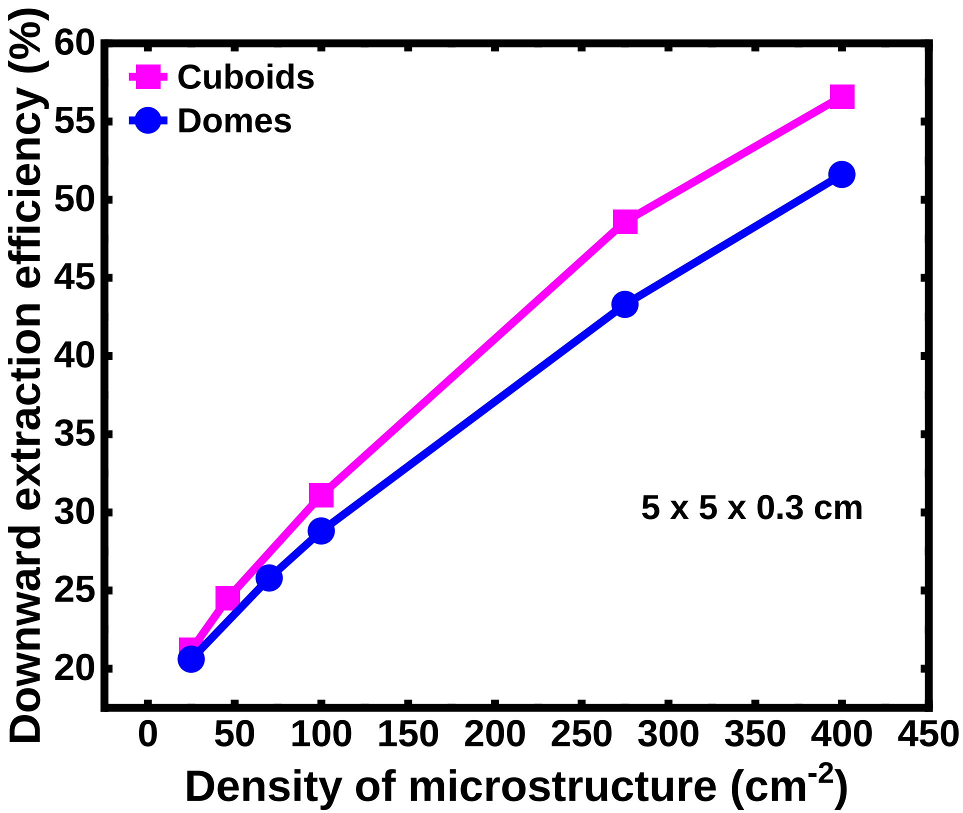
Impact of geometric shape on DE efficiency



- Tapered structures (pyramids, cones, domes) show lower DE than cuboids
- DE rises with pyramid faces, nearing that of cones, which have the highest DE
- Consistent with Shen et al. (2022), where DE follows: domes > cones > pyramids > prisms

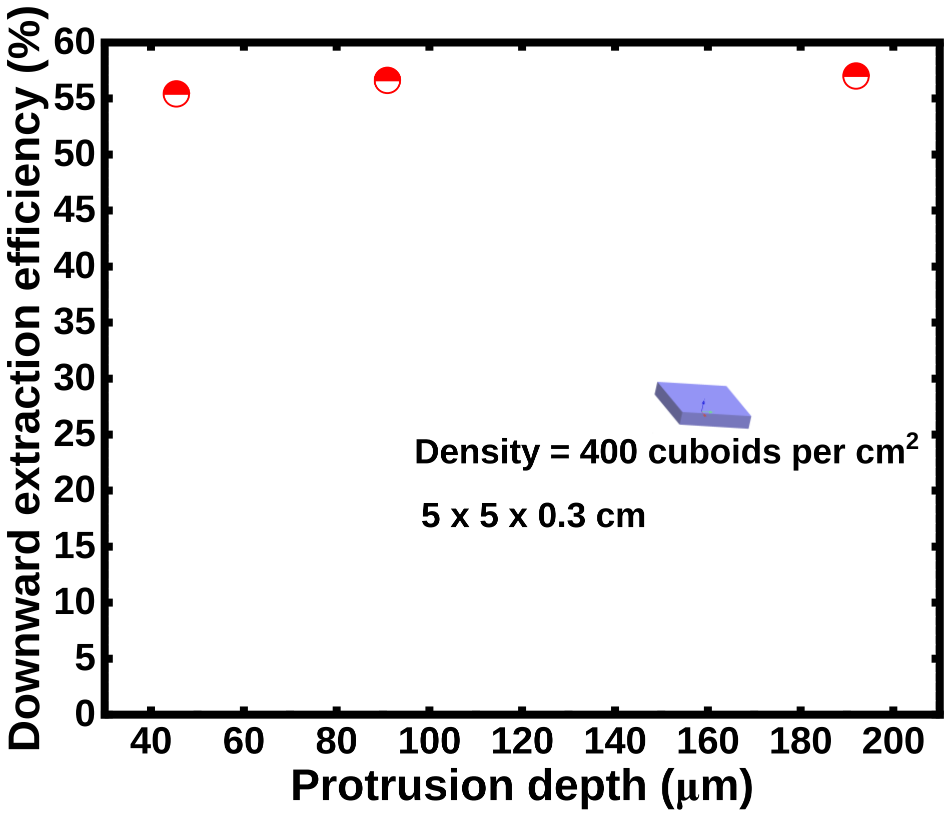
L. Shen, R. Lou, and X. Yin, "Asymmetrical interface design for unidirectional light extraction from spectrum conversion films," Opt. Express **30**, 4642 (2022).

Effect of micro-structure density on DE efficiency



- Increasing density enhances DE due to more frequent ray–structure interactions
- Micro-cuboids exhibit higher DE efficiency than micro-domes at equal density

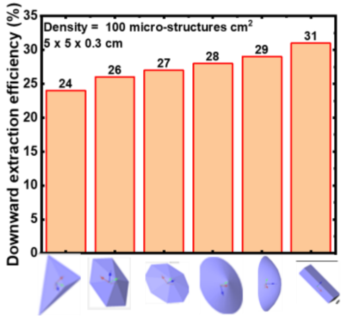
Effect of micro-cuboid indentation depth on DE



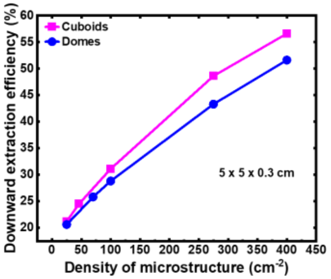
- Slight DE improvement despite large indentation depth depth increase
- Indentation depth is not a critical parameter during fabrication

Conclusion and outlook

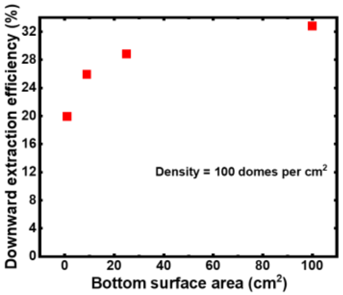
- All investigated shapes enhanced downward extraction (DE) efficiency



- At equal density, micro-cuboids outperformed domes and pyramids with 57% DE



- DE increased with area, supporting upscaling



Acknowledgment

Thank you for your attention!

I would be happy to answer any questions you may have

(juvertfru@gmail.com)

Seed questions

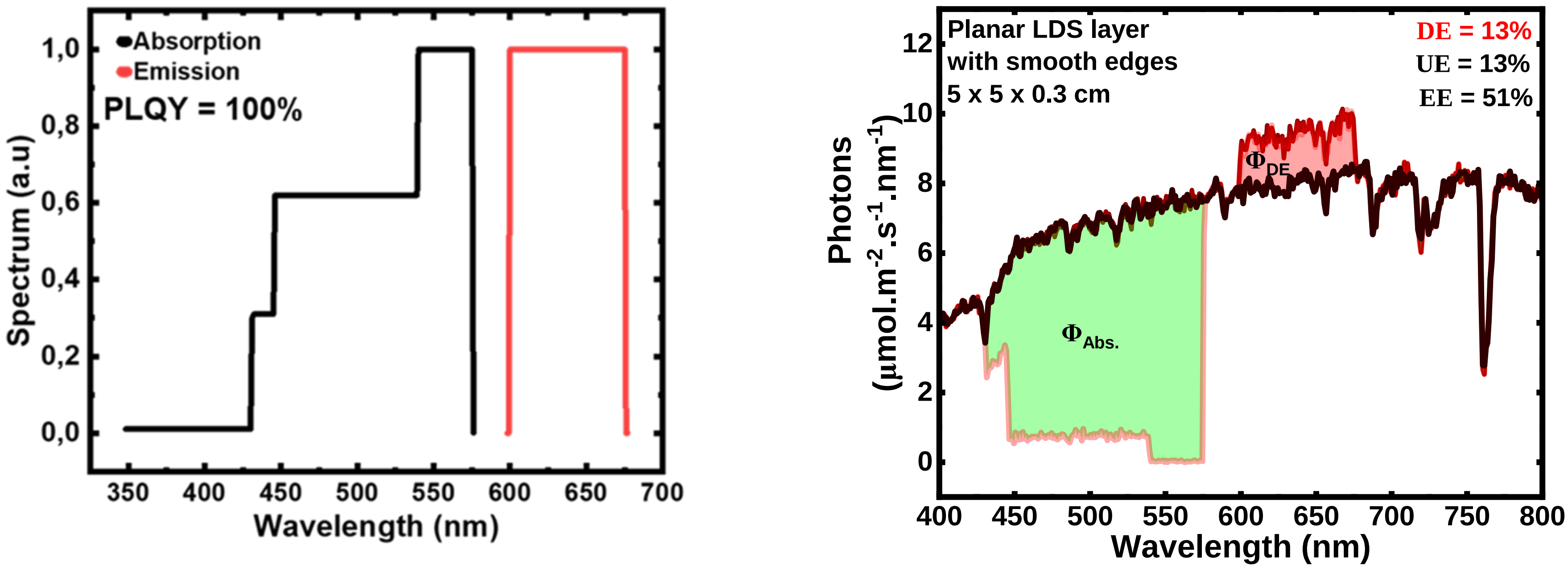
- What are the dominant loss mechanisms in LDS layers used in greenhouse systems?
- Are upconversion materials currently being explored as phosphors for luminescent downshifting layers in greenhouses?

Xu, Z., Yu, Y. and Papakonstantinou, I., 2025. Performance Metrics and Loss Mechanisms in Horticulture Luminescent Solar Concentrators. *IEEE Journal of Selected Topics in Quantum Electronics*

Yanykin, D.V., Burmistrov, D.E., Simakin, A.V., Ermakova, J.A. and Gudkov, S.V., 2022. Effect of up-converting luminescent nanoparticles with increased quantum yield incorporated into the fluoropolymer matrix on solanum lycopersicum growth. *Agronomy*, *12*(1), p.108

Backup Slides

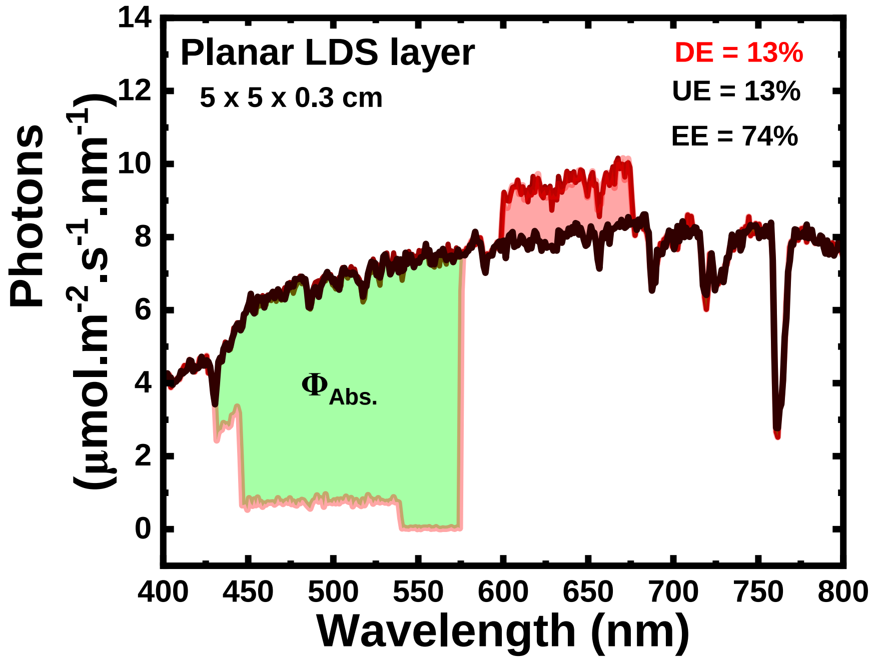
Spectra and simulated irradiance for an ideal planar LDS layer



(a) Absorption and emission spectra of the model dye, illustrating complete spectral separation, and
(b) simulated solar irradiance profile for an ideal planar luminescent downshifting (LDS) layer with smooth edges (Total extraction = 13% +13% + 51%)

- With smooth edges, roughly 23% of emitted photons remain trapped in the LDS layer due to repeated total internal reflection

Simulated irradiance of an ideal LDS layer with scattering edges



Simulated solar irradiance profile for an ideal planar luminescent downshifting (LDS) layer with scattering edges (TE = 13% + 13% + 74% = 100%)

- Edge scattering breaks total internal reflection at edges, enabling full extraction of the emitted photons