Surprising Nanophotonic Phenomena in Nature

NCN SURF

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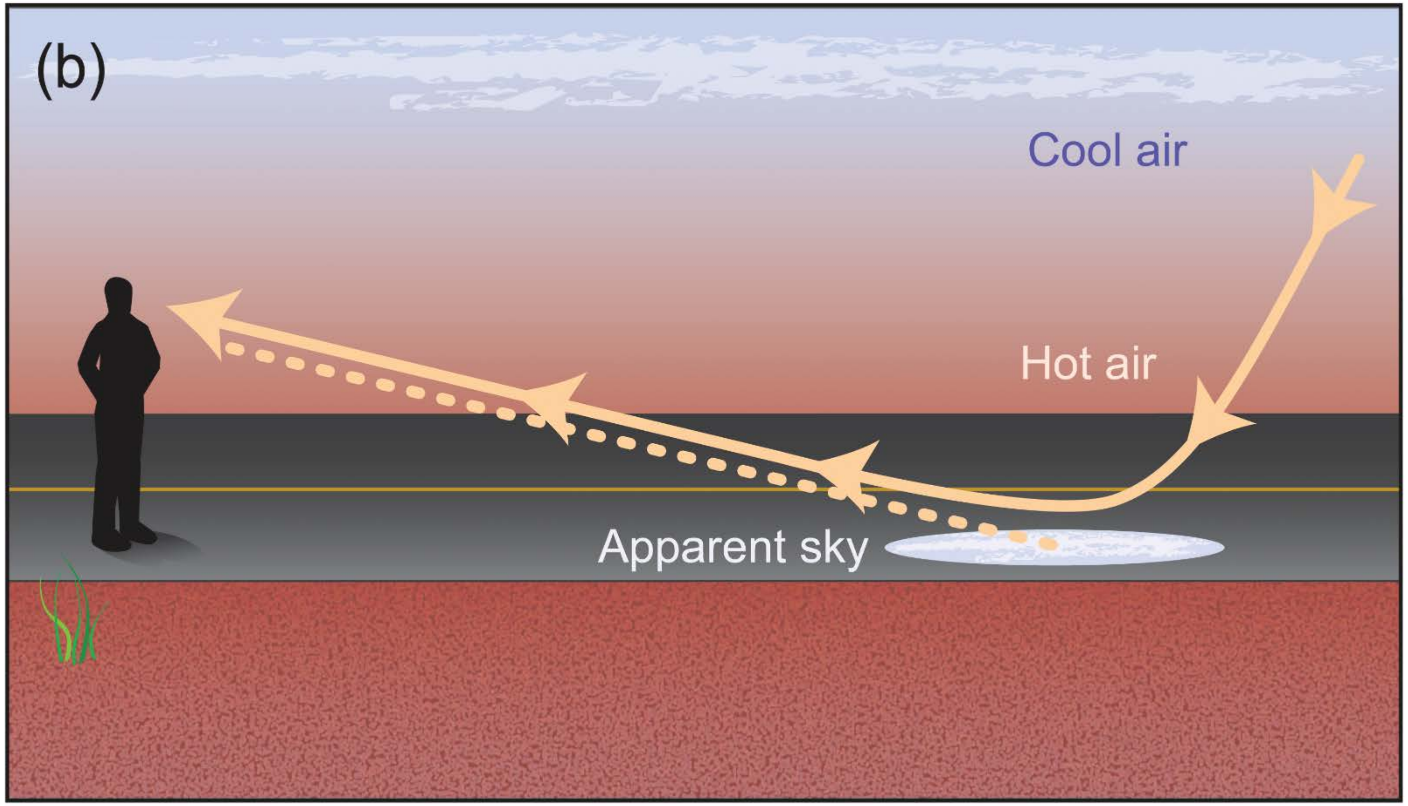
Inferior Mirages

An inferior mirage from Florida sunset, Michael Menefee on Flickr

Inferior mirage on highway from Weatherstock.com

Inferior Mirages

When you see a mirage, you are actually seeing a reflection of the sky on the ground



http://sciencebasedlife.wordpress.com/2012/03/19/what-is-a-mirage/

Superior Mirages

Superior mirages of tanker and islands in Finland
(http://virtual.finland.fi/finfo/english/mirage.html)
http://www.astronomycafe.net/weird/lights/mirgal.htm

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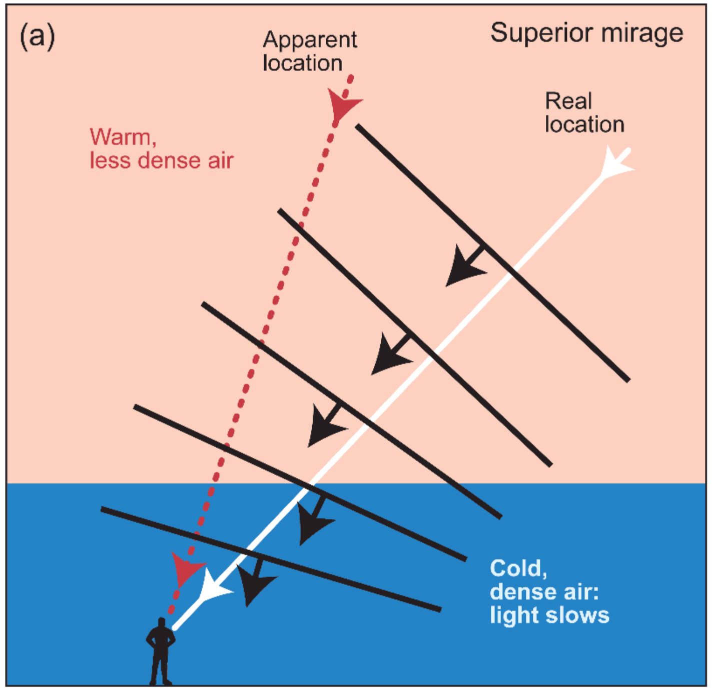
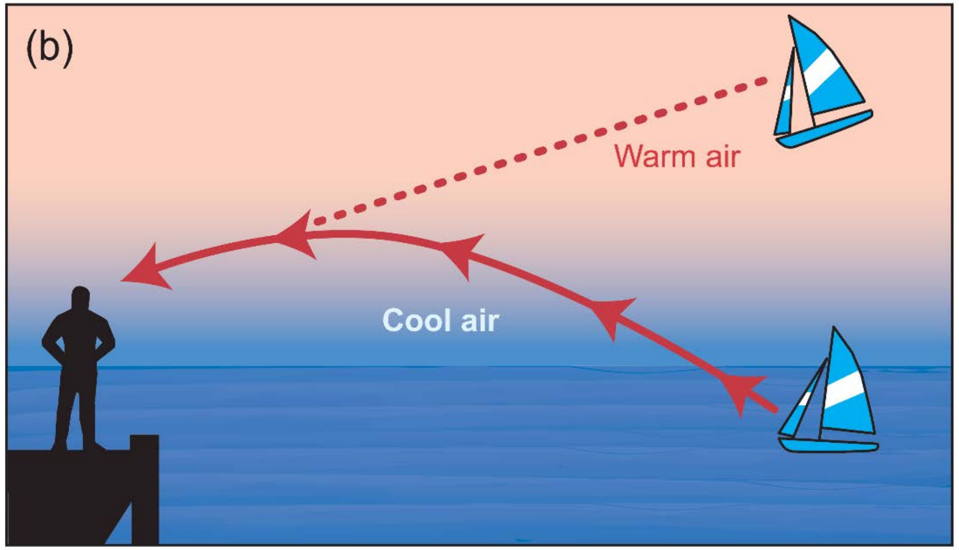
Superior Mirages





http://nsidc.org/arcticmet/basics/phenomena/superior_mirage.html

Application: Long-Distance Telecommunications

Combine 2 types of mirages for long-distance communications in a graded-index fiber

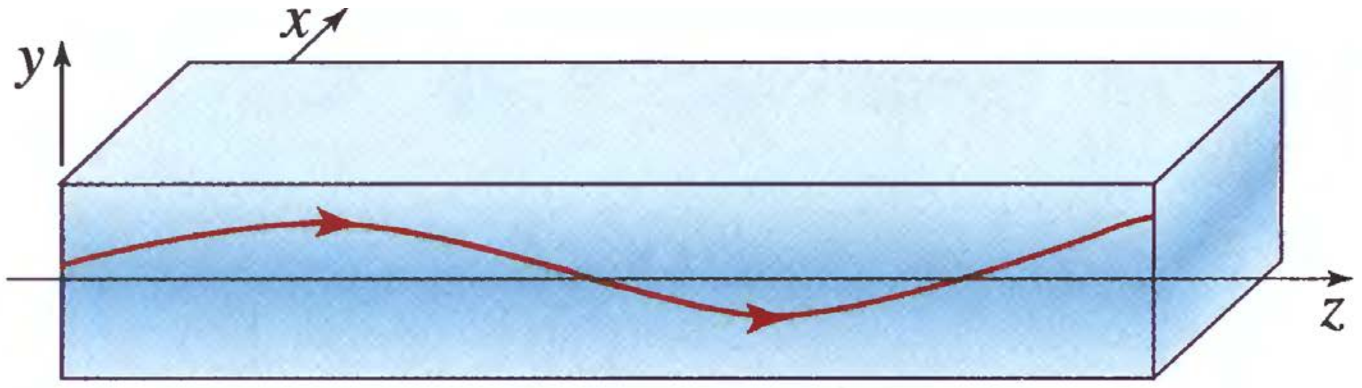
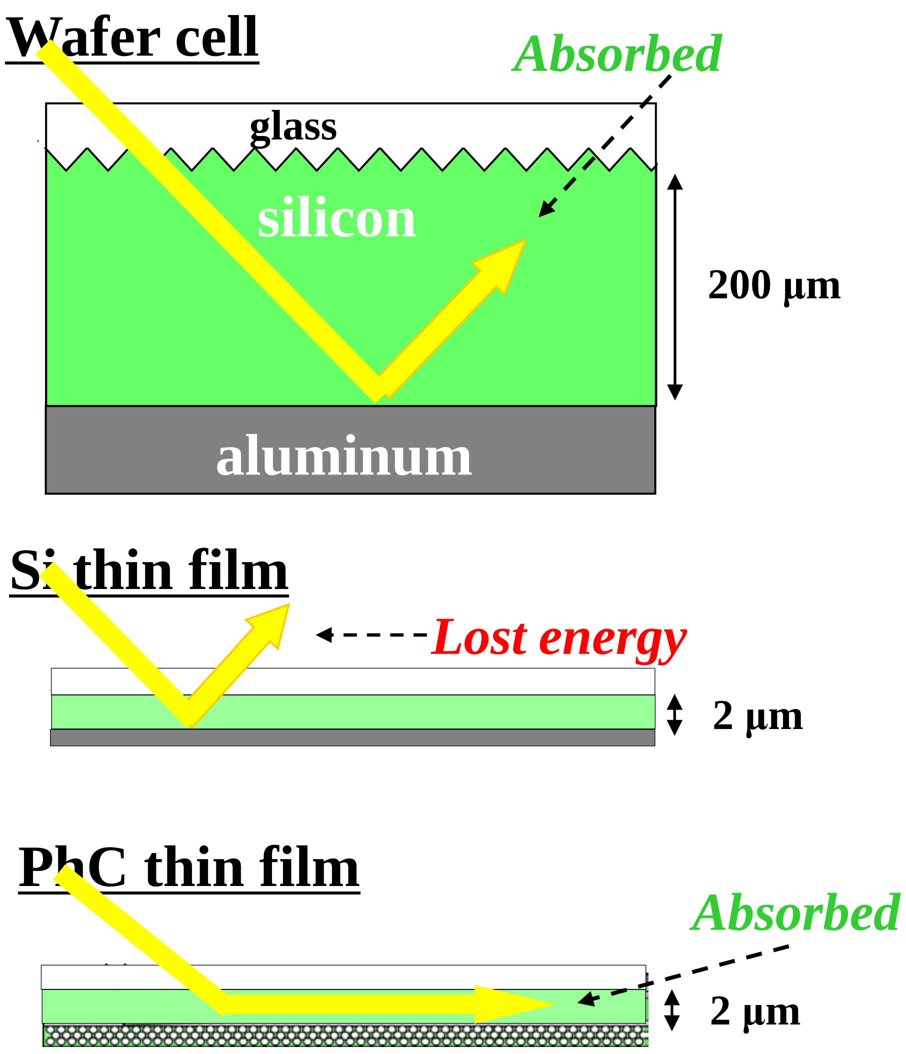
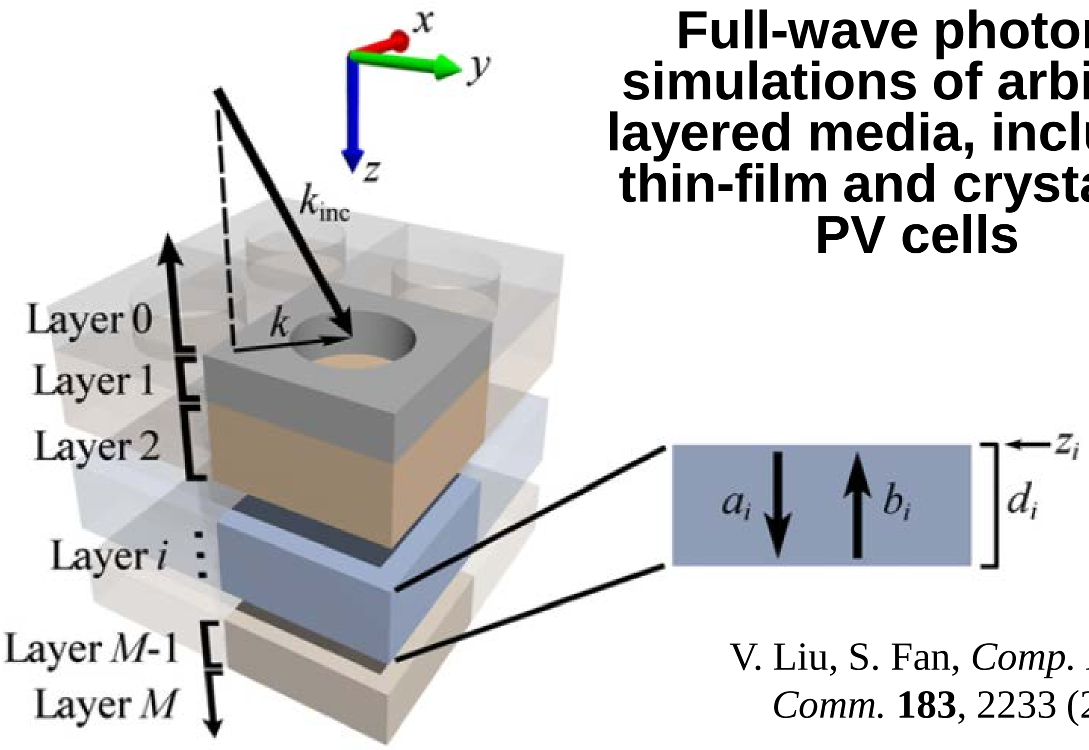


Figure 1.3-2 Trajectory of a paraxial ray in a graded-index medium.

Application: Improving Solar Cells



Photonic Simulations with S^4



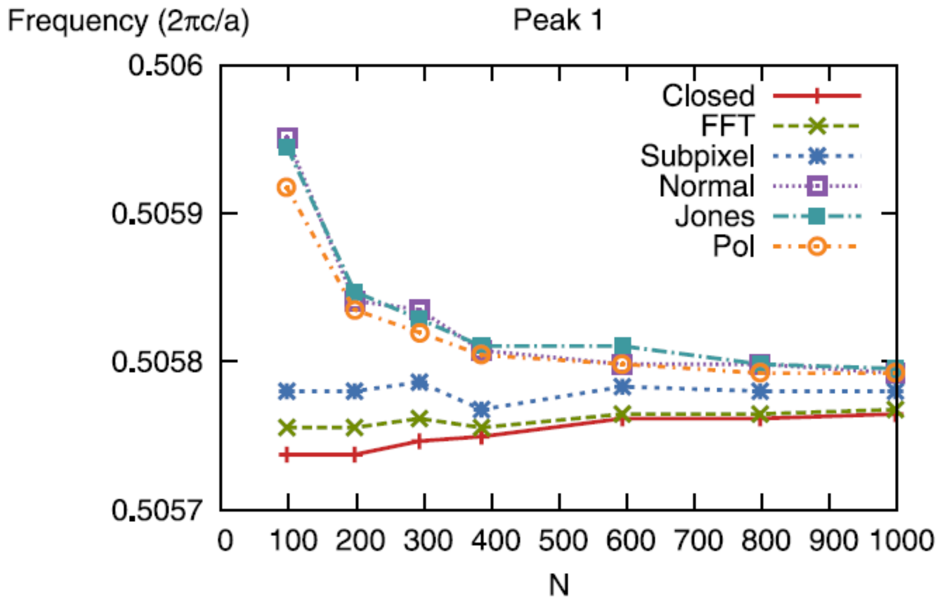
Full-wave photonic simulations of arbitrary layered media, including thin-film and crystalline PV cells

V. Liu, S. Fan, *Comp. Phys. Comm.* **183**, 2233 (2012)

https://nanohub.org/tools/s4sim/

Photonic Simulations with S^4

Accuracy improves systematically
with computing power



V. Liu, S. Fan, *Comp. Phys. Comm.* **183**, 2233 (2012)

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S⁴: Lua Control Files

Obtain a new, blank simulation object with no solutions:

```
S = S4.NewSimulation()
```

Define all materials:

```
S:AddMaterial('name', {eps_real, eps_imag})
```

Add all layers:

```
S:AddLayer('name', thickness, 'material_name')
```

Add patterning to layers:

```
S:SetLayerPatternCircle('layer_name', 'inside_material',
{center_x, center_y}, radius)
```

S^4: FMM Formulations

Specify the excitation mechanism:

```
S:SetExcitationPlanewave(
        {angle_phi, angle_theta}, -- phi in [0,180), theta in [0,360)
        {s_pol_amp, s_pol_phase}, -- phase in degrees
        {p_pol_amp, p_pol_phase})
```

Specify the operating frequency:

```
S:SetFrequency(0.4)
```

Obtain desired output:

```
forward_power, backward_power = S:GetPoyntingFlux('layer_name', z_offset)
print(forward_power, backward_power)
```


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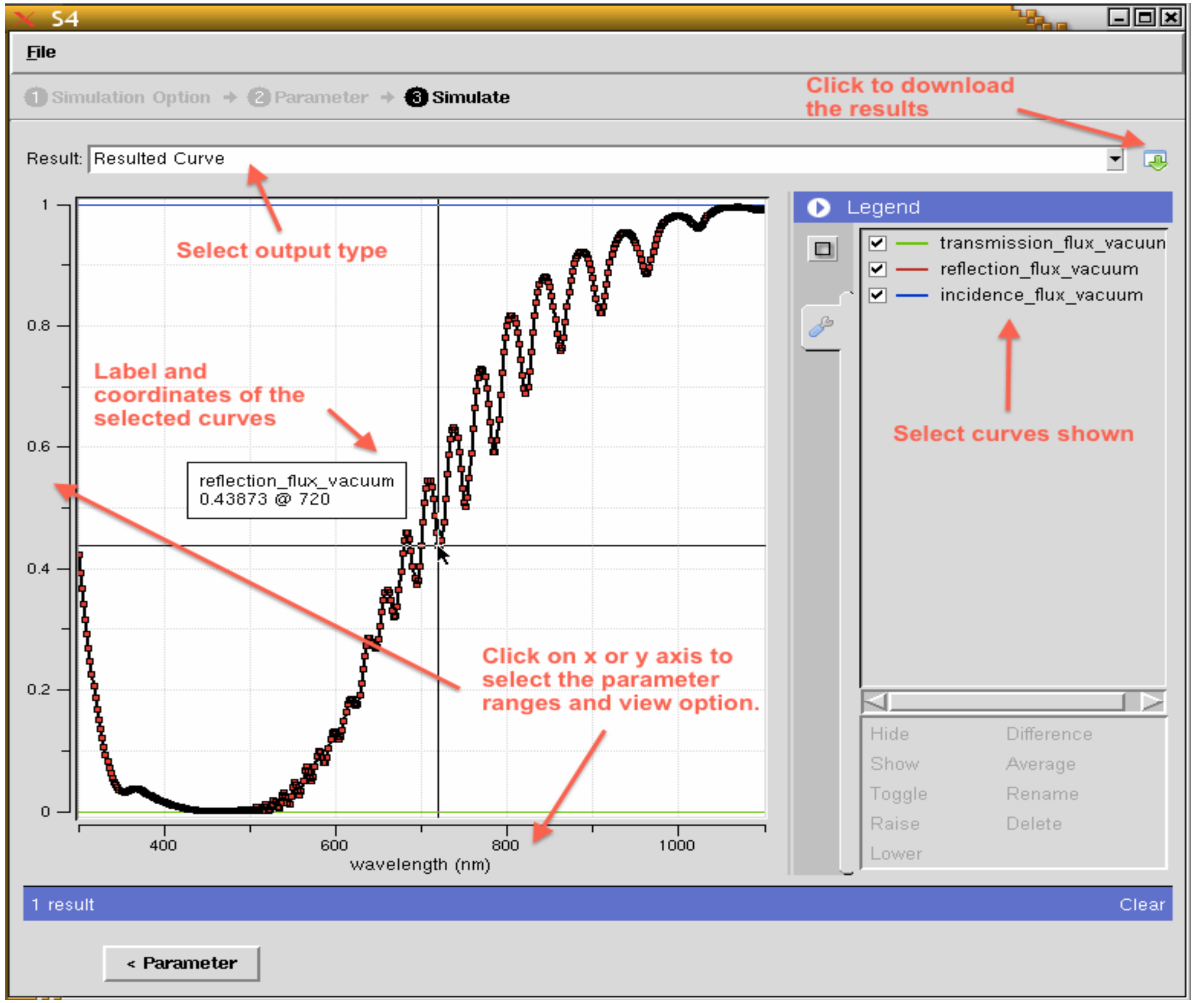
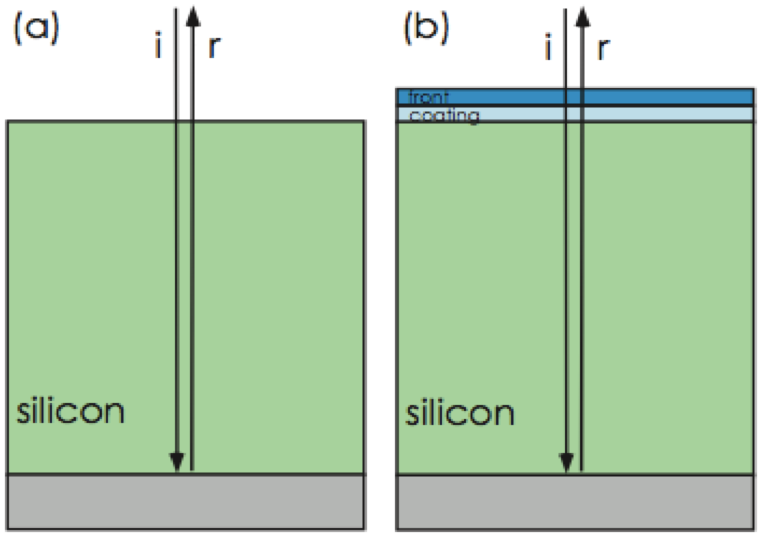
S4sim: Output Window



S4sim Example: PV Front Coating



Number of front coating layers	1		2		3	
Relative permittivity	Real	Imag	Real	Imag	Real	Imag
Layer 1 Layer 2 Layer 3	4.32	0	2.37 9.12	0 0	1.80 5.71 14.36	0 0 0

Number of front coating layers	1	2	3
Thickness (nm) Layer 1 Layer 2 Layer 3	60	82.3 38.9	91.0 53.1 29.9

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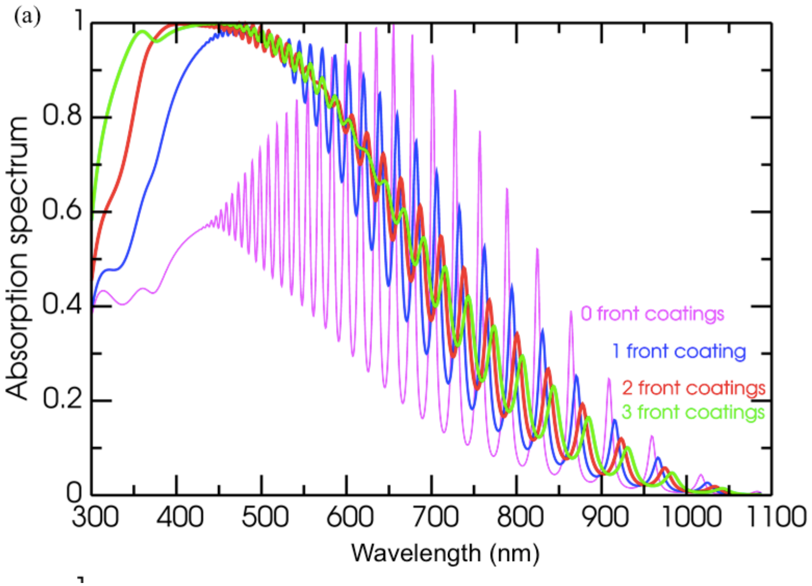
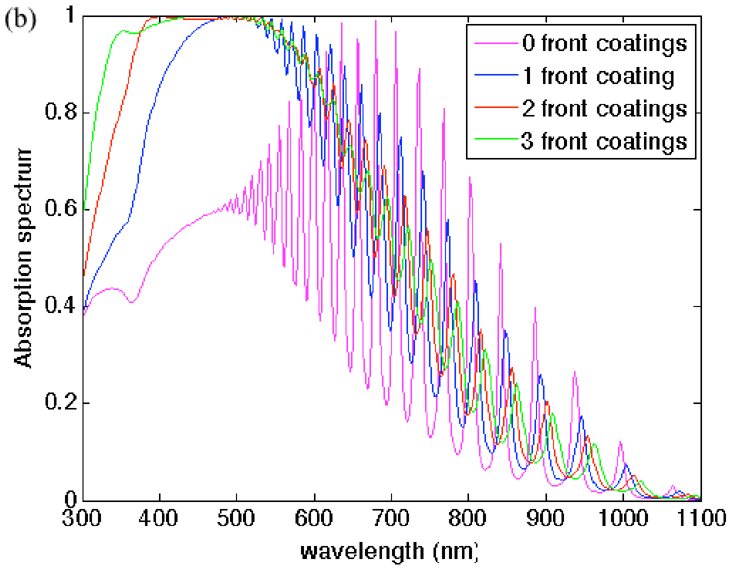
S4sim Example: PV Front Coating



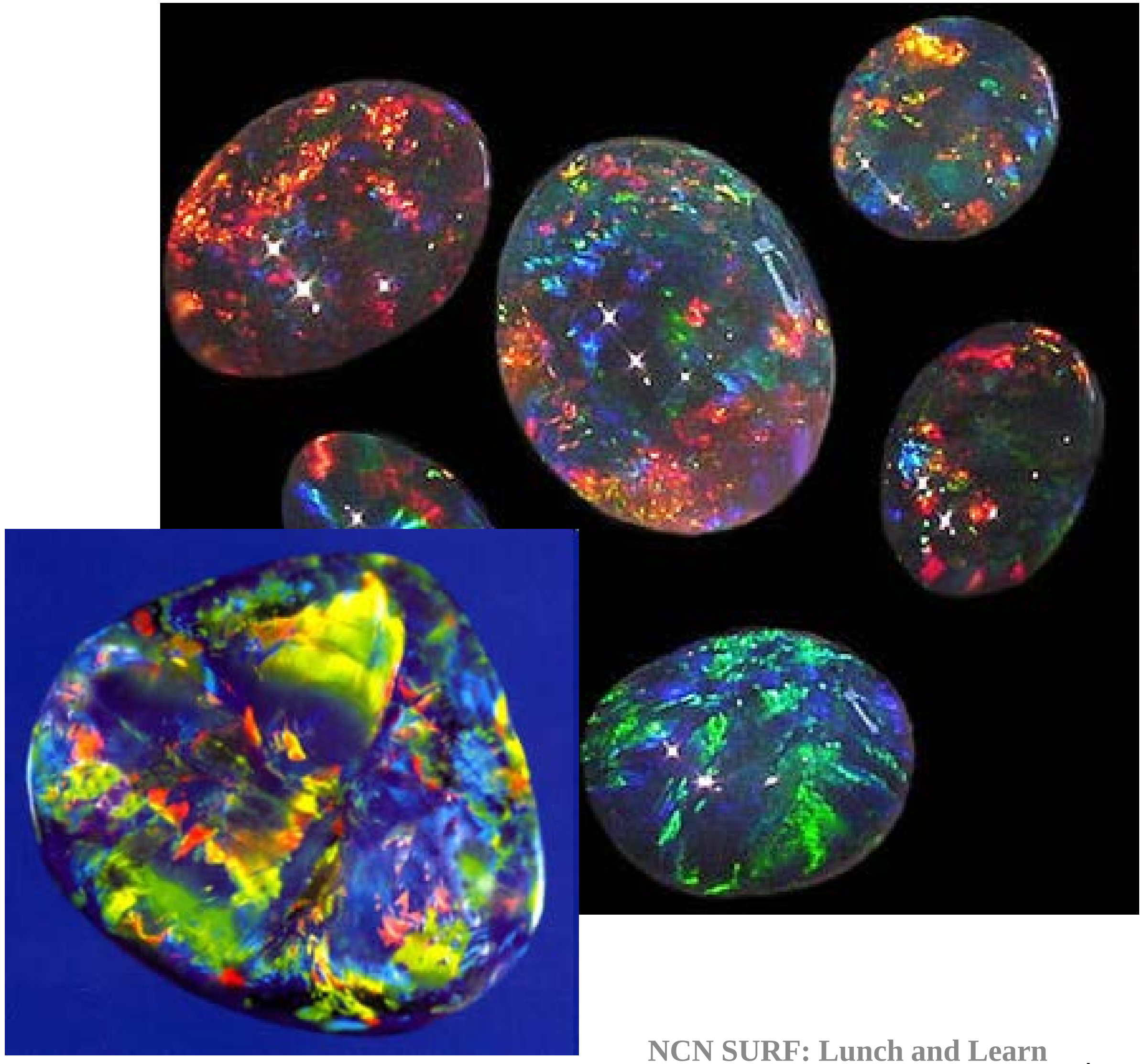
Results from M. Ghebrebrhan, P. Bermel, Y. Avniel, J. Joannopoulos, and S. Johnson, Optics Express 17, 7505-7518 (2009).



Results generated by S4sim

Nature was the First…

Natural opal



Artificial direct and inverse opals

http://www.australianblackopals.com/images
http://www.opals-of-light-and-fire.com/web_images/black-opal-1.jpg

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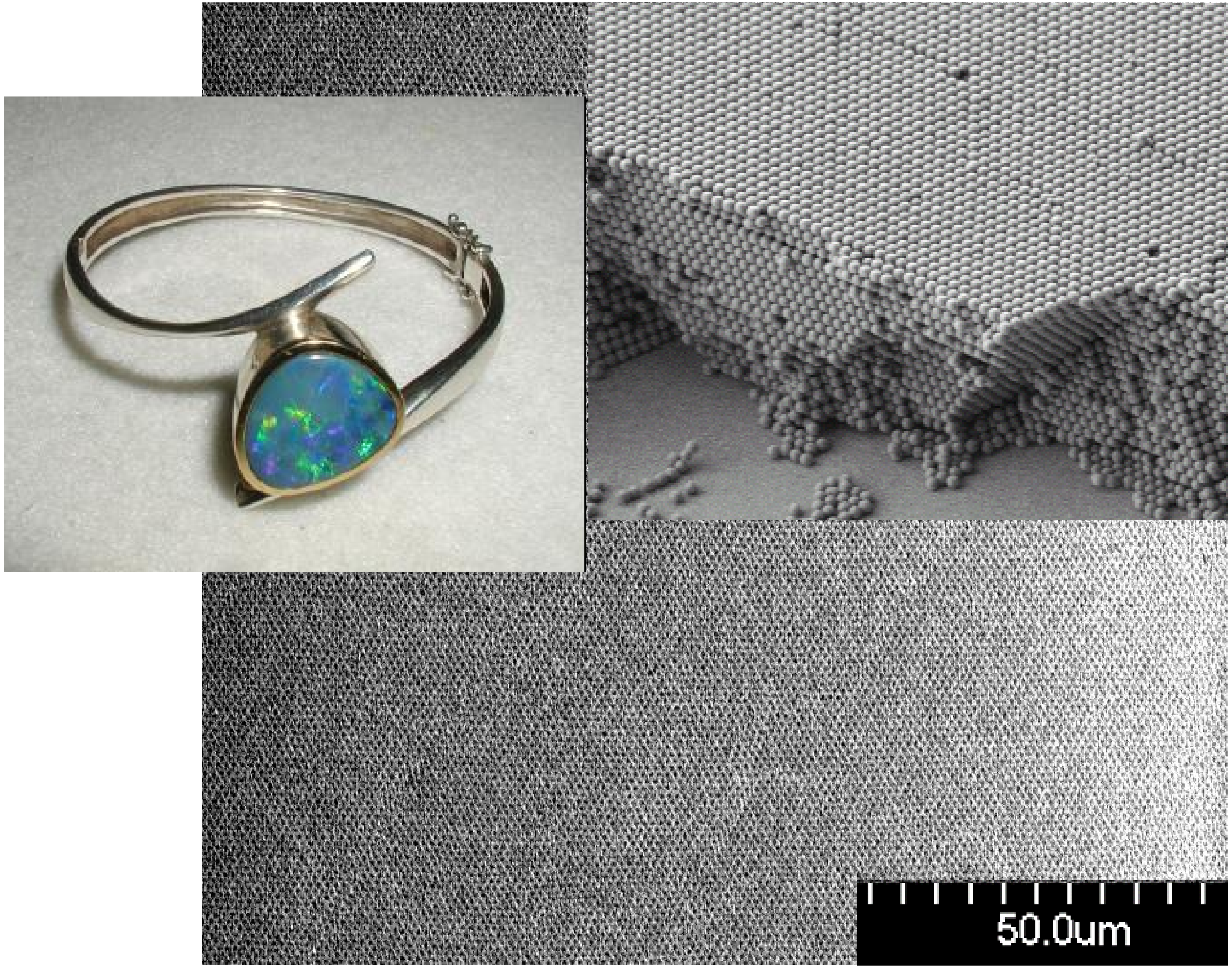
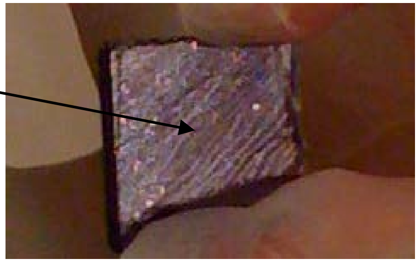
Self-Assembled 3D Photonic Crystal Structures: Opals

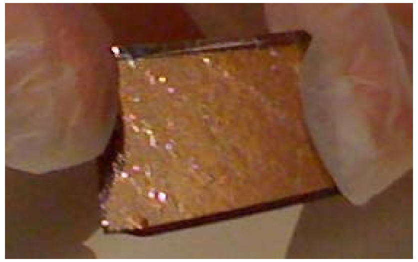


Benefits of Opal PhCs in Solar Cells

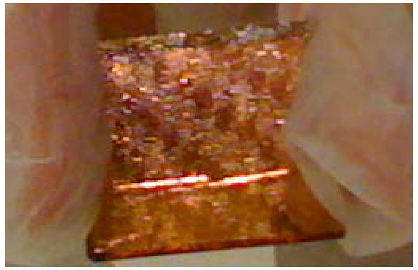
Noticeably darker than controls!



Expt'l cell with texturing and PhC



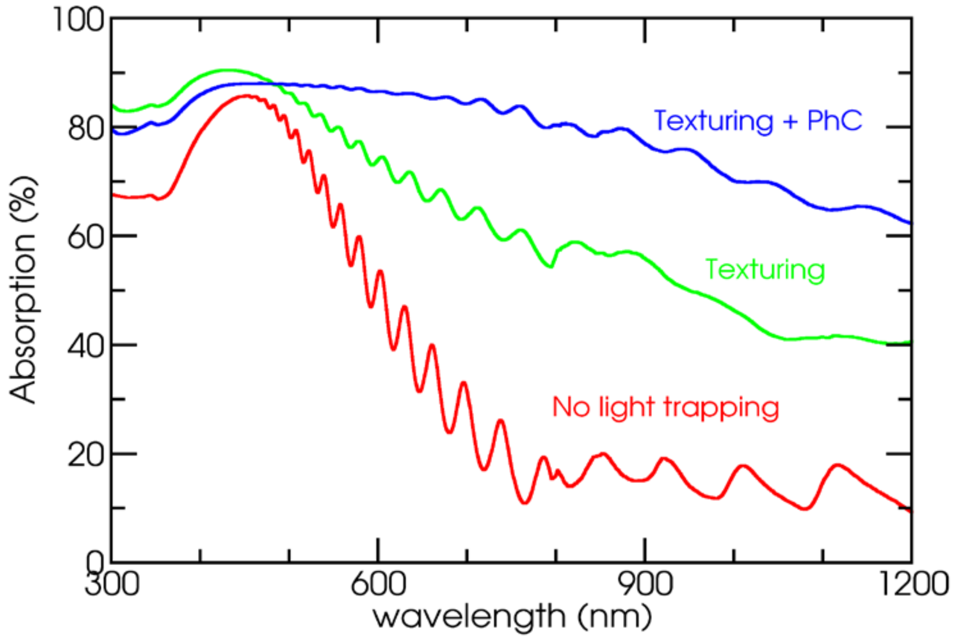
Control cell with texturing



Control cell without light trapping

PhC enhanced cell →

30% higher J_{sc} than texturing



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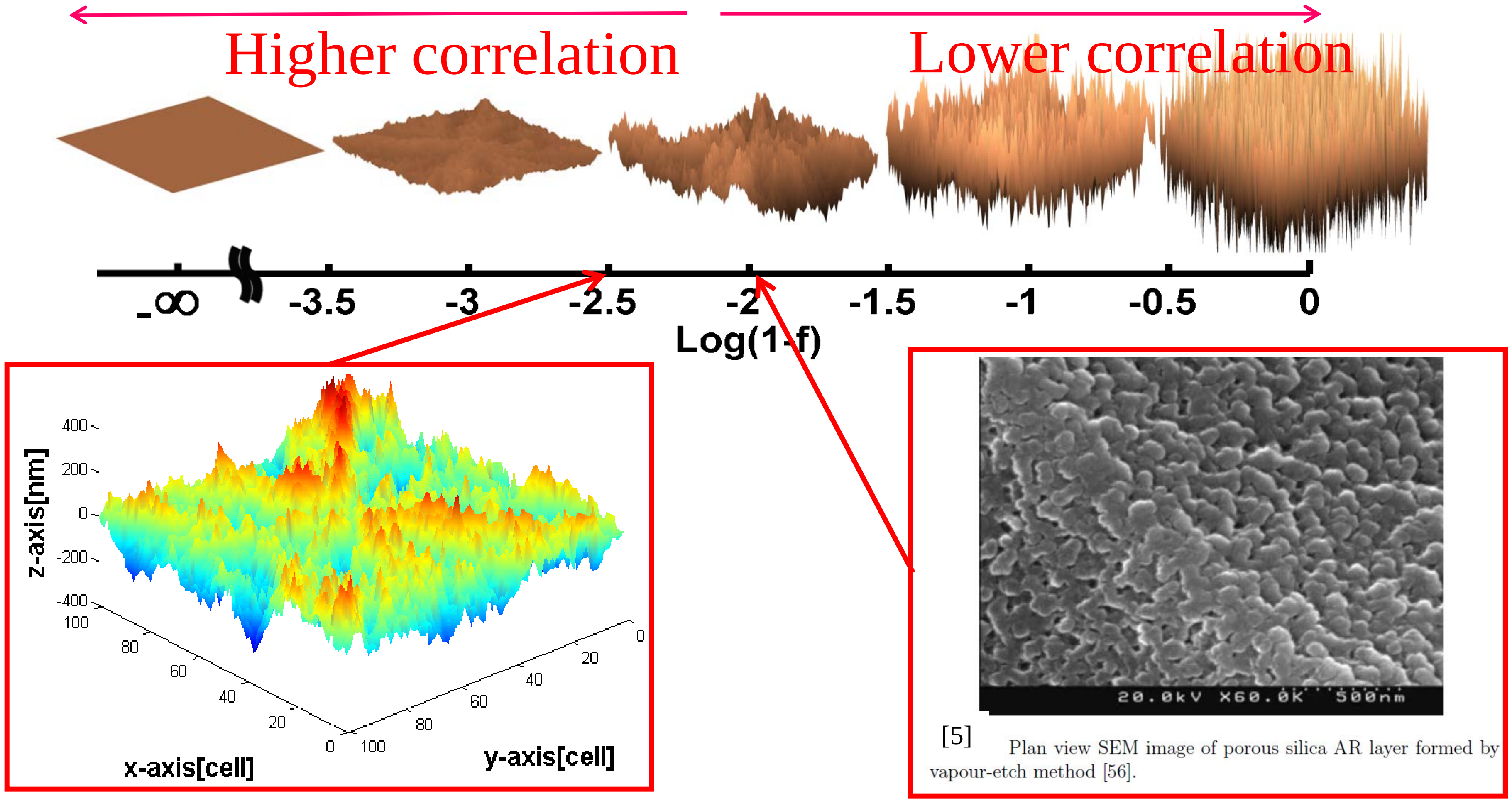
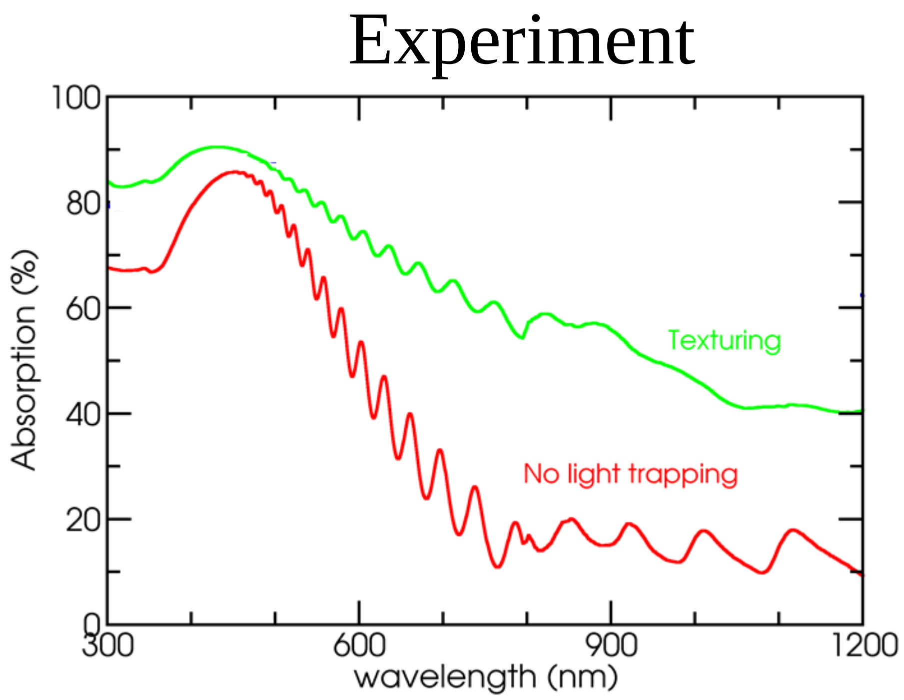
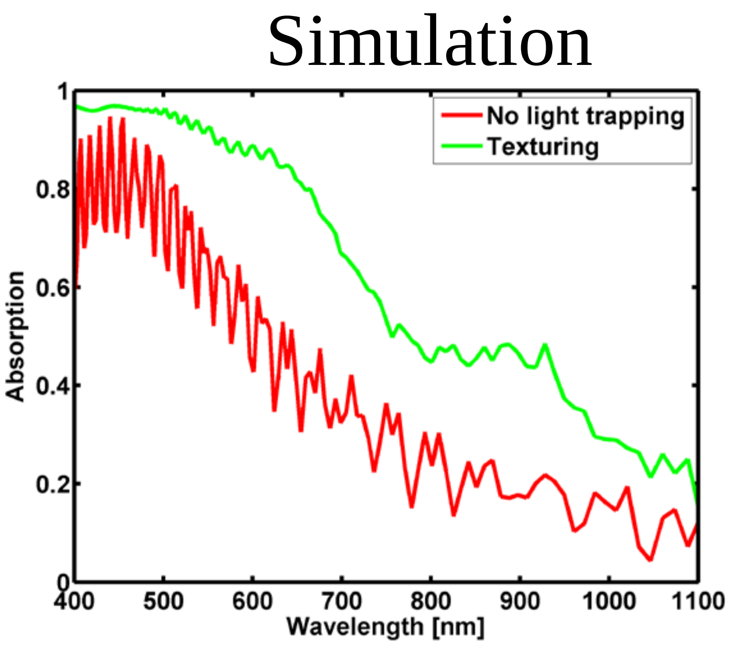
From the flat structure to the totally random structure via random surface texturing algorithm



[5] Keevers, M. J., et al. "10% efficiency CSG minimodules." *Proceedings of the 22nd European Photovoltaic Solar Energy Conference.* (2007).

Experimental absorption vs simulated absorption





- The left figure indicates the experimental absorption rate for a 1500 nm thick c-Si solar cell. It is adapted from recently published research [4]. The right figure indicates the absorption rate obtained by the simulation.
- 3-D QCRF-FDTD simulation is performed using the same geometry in order to prove its accuracy

[4] L. T. Varghese, Y. Xuan, B. Niu, L. Fan, P. Bermel, and M. Qi, "Enhanced photon management of thin-film silicon solar cells using inverse opal photonic crystals with 3d photonic bandgaps," Advanced Optical Materials 1, 692–698 (2013).

Refraction: Epsilon Near Zero

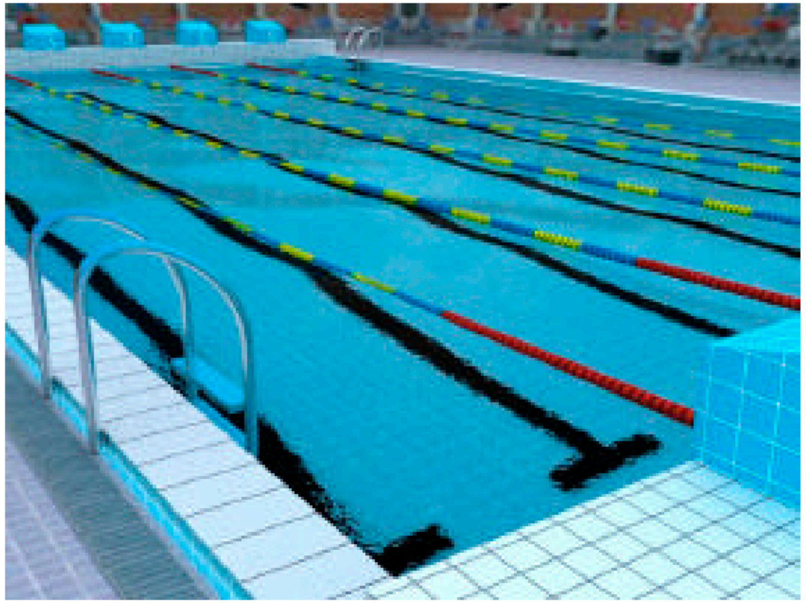


Image of a swimming pool filled with water (*n*=1.33) (computer-generated)

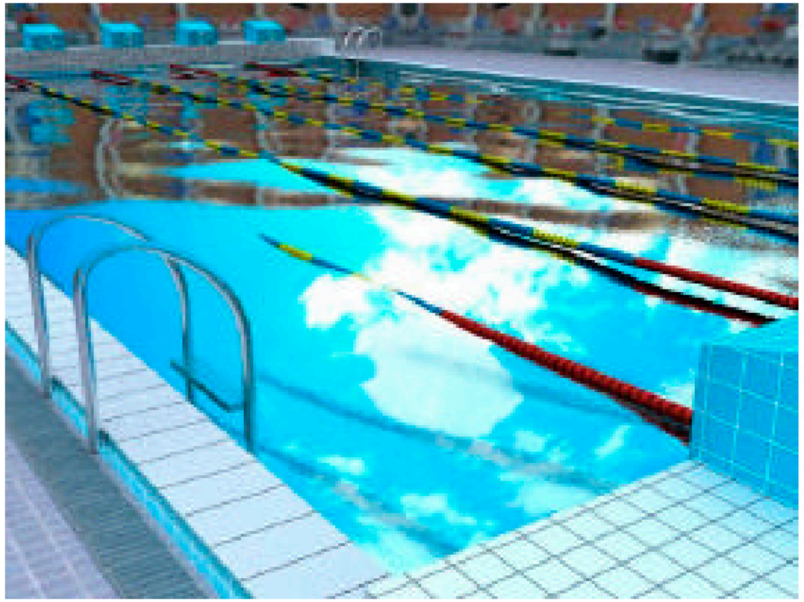
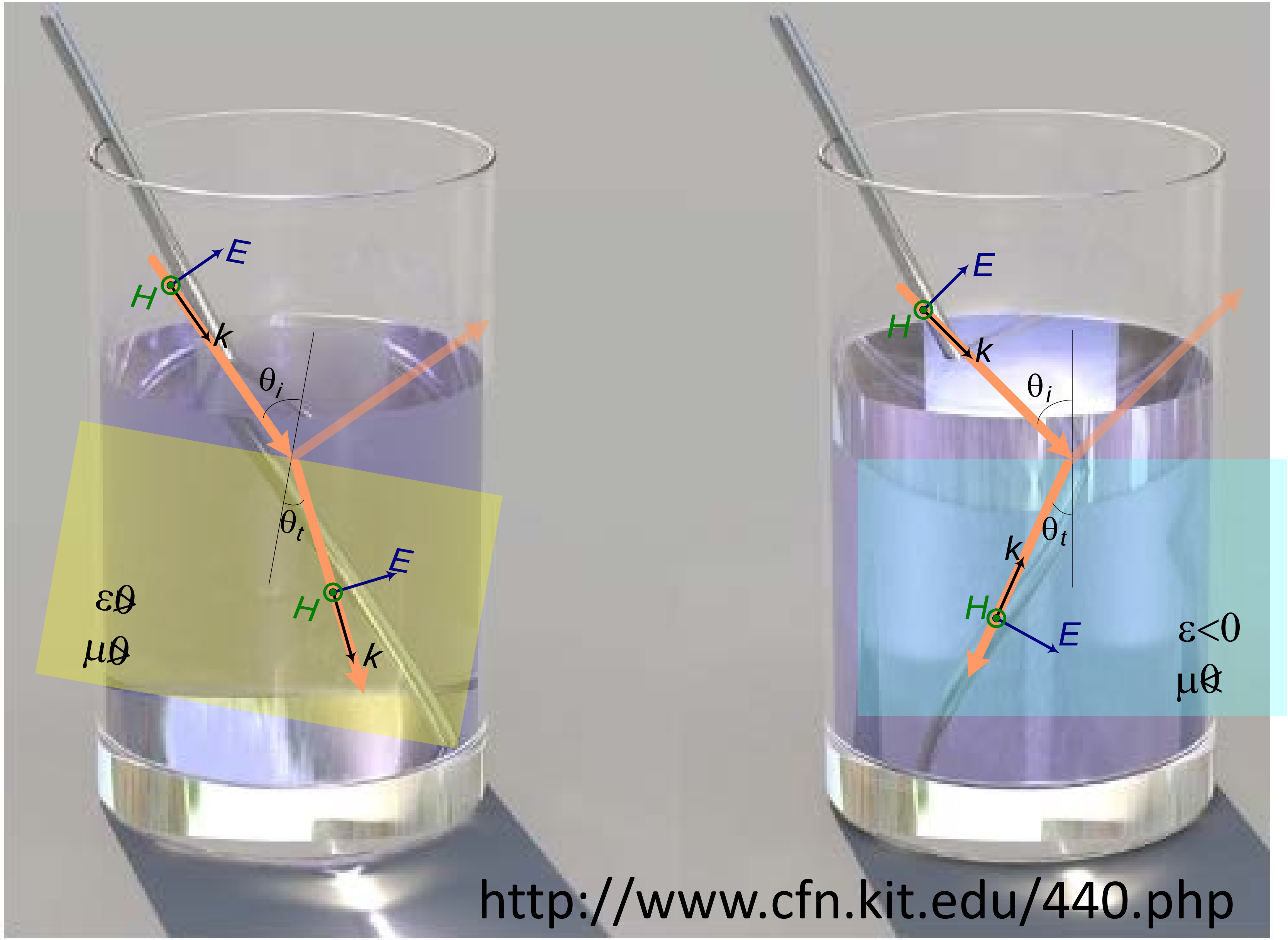


Image of a swimming pool filled with a substance having *n*=0.9.

Aaron Danner, **"Photorealistic ray tracing aids understanding of metamaterials,"** 12 March 2009, SPIE Newsroom. DOI: 10.1117/2.1200903.1525

Negative Refractive Index



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Refraction: Negative Index

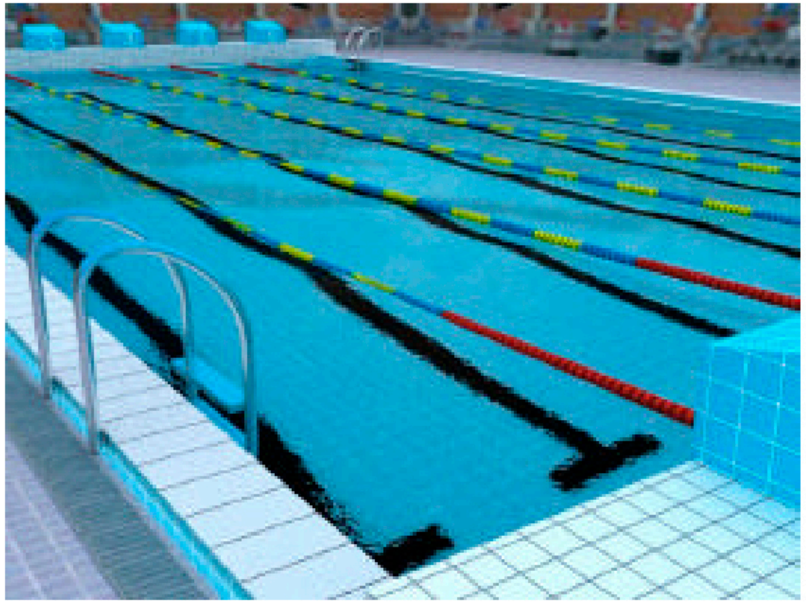
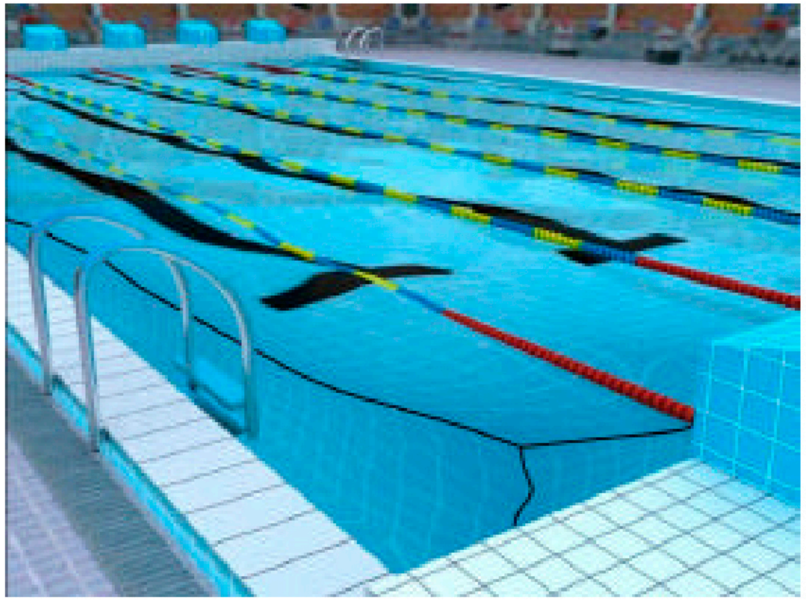


Image of a swimming pool filled with water (*n*=1.33) (computer-generated)



Pool filled with negative-index 'water' (n=- 1.33). A black line: location of the pool bottom edge and corner. The bottom of the pool seems to 'float' above ground level.

Aaron Danner, **"Photorealistic ray tracing aids understanding of metamaterials,"** 12 March 2009, SPIE Newsroom. DOI: 10.1117/2.1200903.1525

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Refraction: Negative Index

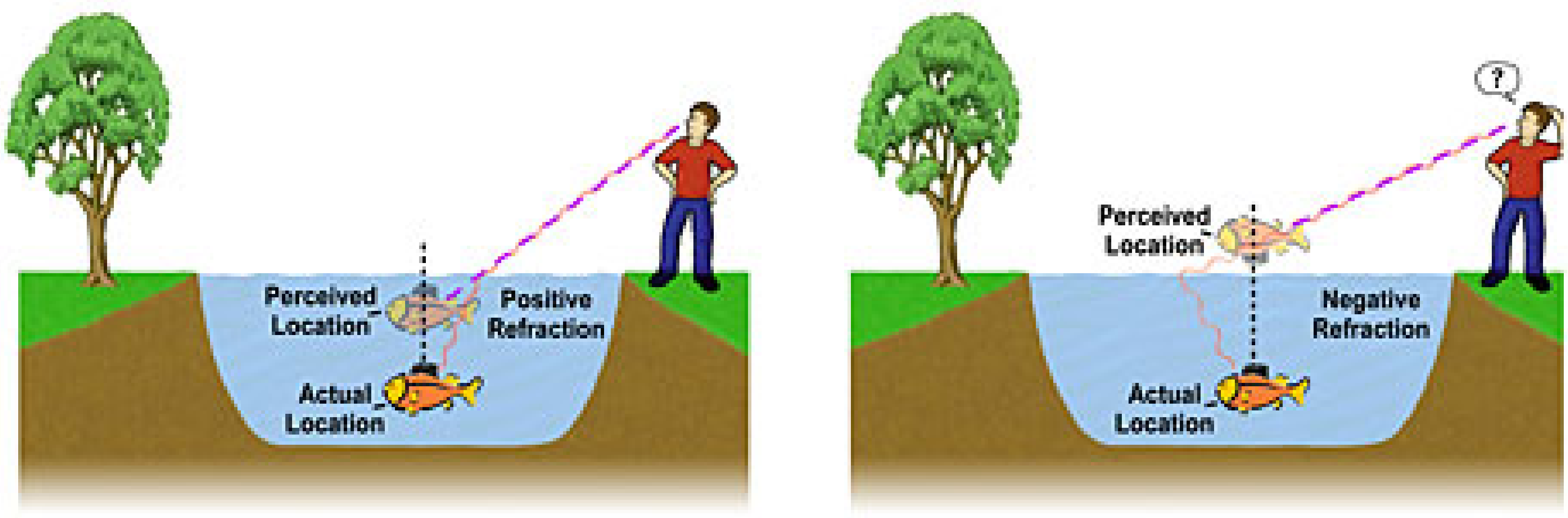
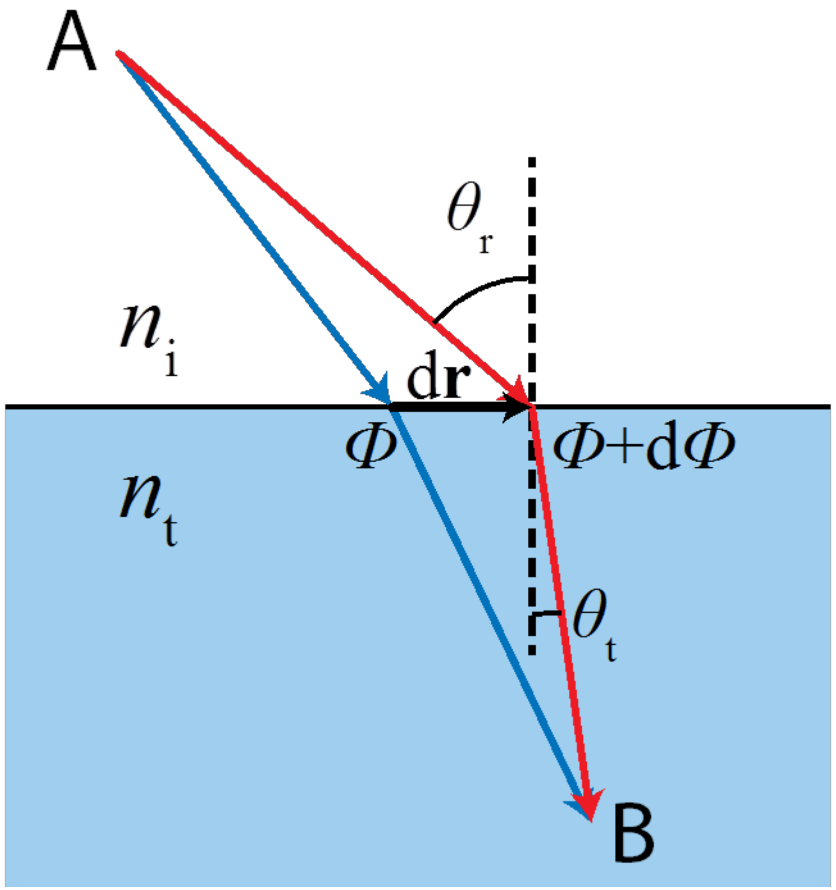


Illustration: UC Berkeley

Generalized Snell's Law



† Landau and Lifshitz, The Classical Theory of Fields (4 ed.)

Principle of least action → The momenta difference between blue and red path is zero

$$(n_i \mathbf{k}_0 \sin\theta_i + \nabla\Phi)\mathrm{d}\mathbf{r}$$
$$-(n_t \mathbf{k}_0 \sin\theta_t)\mathrm{d}\mathbf{r} = 0$$

since $\mathbf{k} = \nabla\Phi$ †

For reflection

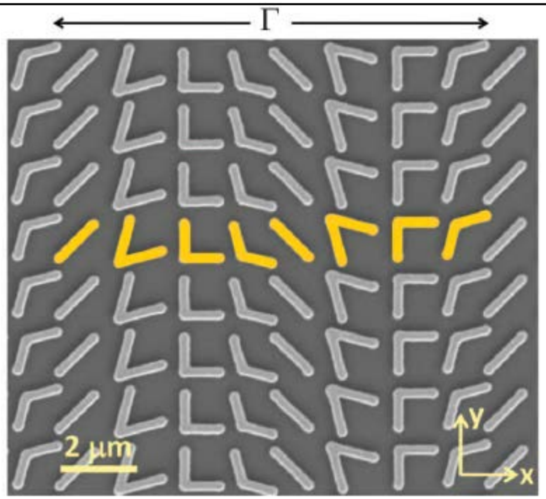
$$\sin\theta_r - \sin\theta_i = n_i^{-1} k_0^{-1} \nabla\Phi$$

For refraction

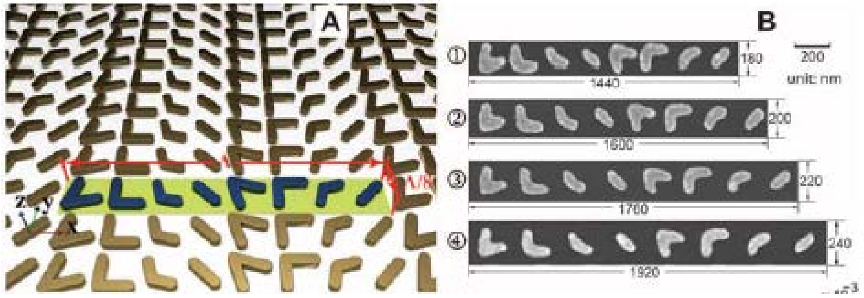
$$n_t \sin\theta_t - n_i \sin\theta_i = k_0^{-1} \nabla\Phi$$

In essence, momentum conservation!

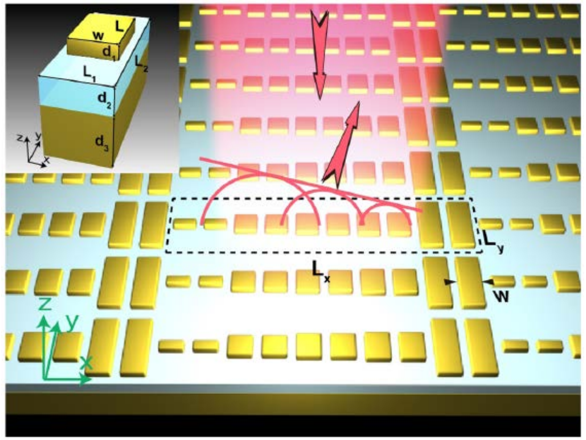
Generalized Snell’s Law: Recent Work



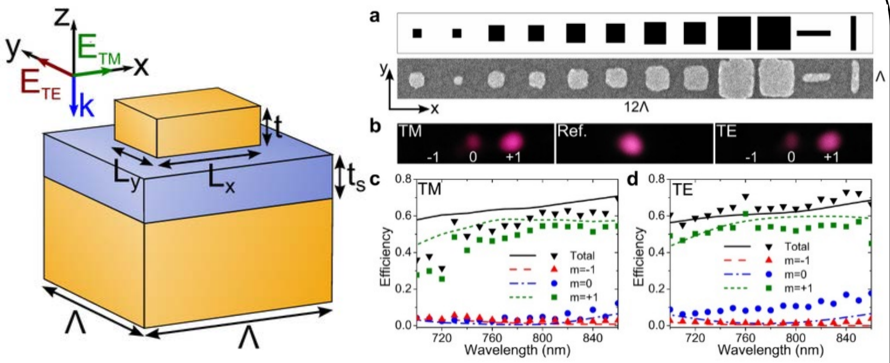
Nanfang Yu *et al*., *Science* **334**, 333 (2011).



Xingjie Ni *et al*., *Science* **335**, 427 (2012).

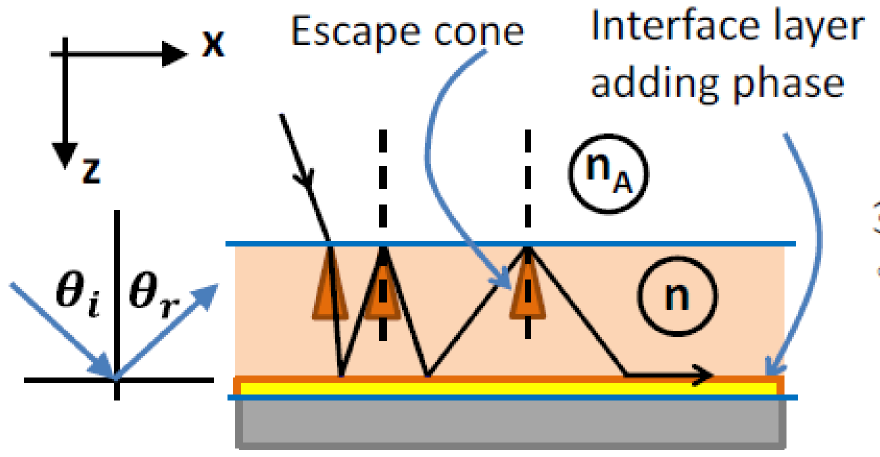


Shulin Sun *et al*., *Nano Lett.* **12**, 6263 (2012).

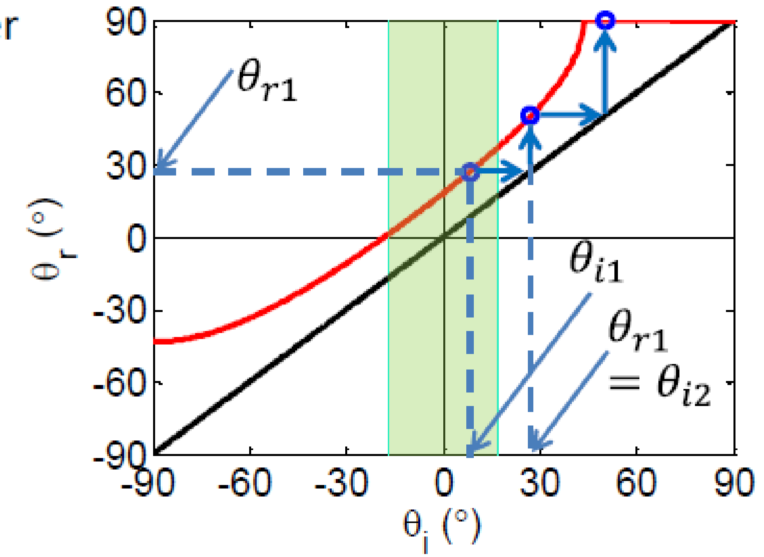


Anders Pors *et al*., *Sci. Rep.* **3**, 2155 (2013).

Ultra-thin Metasurface Absorbers/Emitters

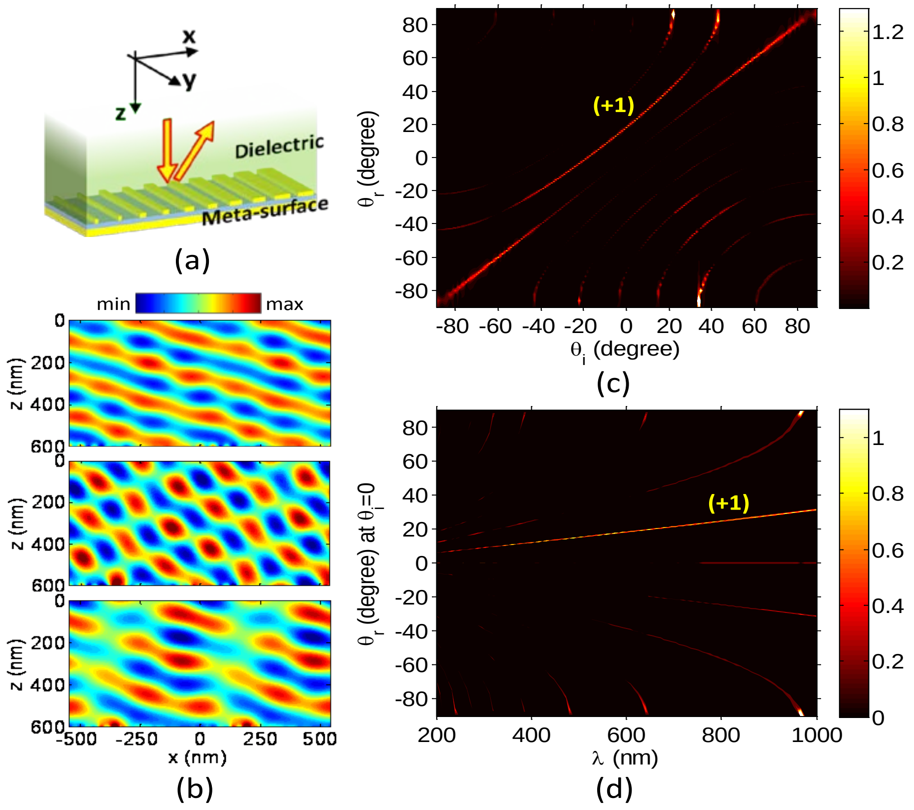


Metasurface bends light at each reflection



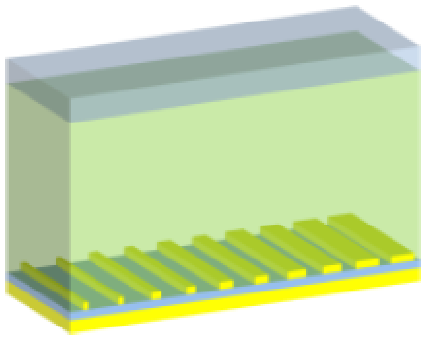
Complete coupling with external radiation in ultrathin layers

S4Sim Example: Xylophone Metasurface for Light Deflection

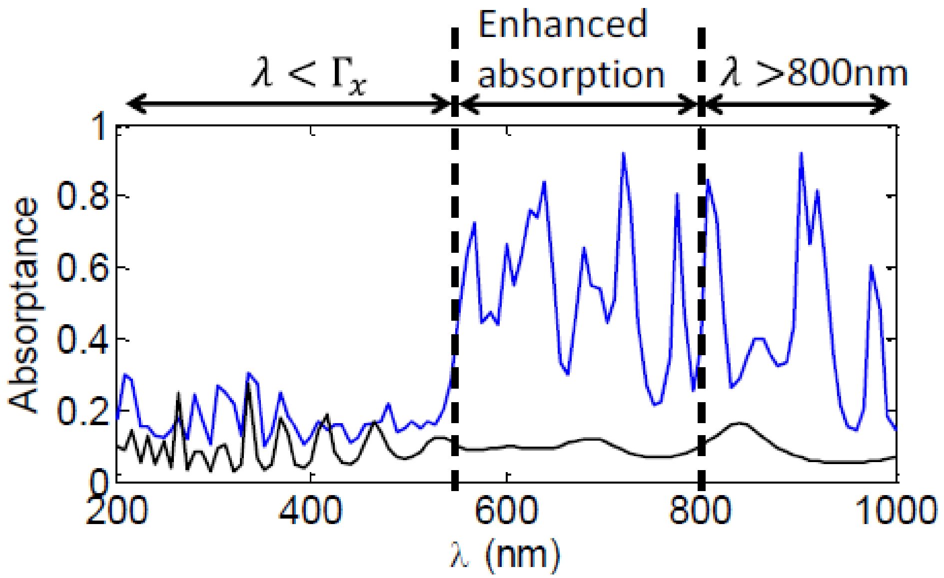


M. Ryyan Khan, Xufeng Wang, Peter Bermel, and Muhammad A. Alam, "Enhanced light trapping in solar cells with a meta-mirror following Generalized Snell's law," *Opt. Express* **22**, A973-A985 (2014).

Xylophone Metasurface: Absorption Enhancement



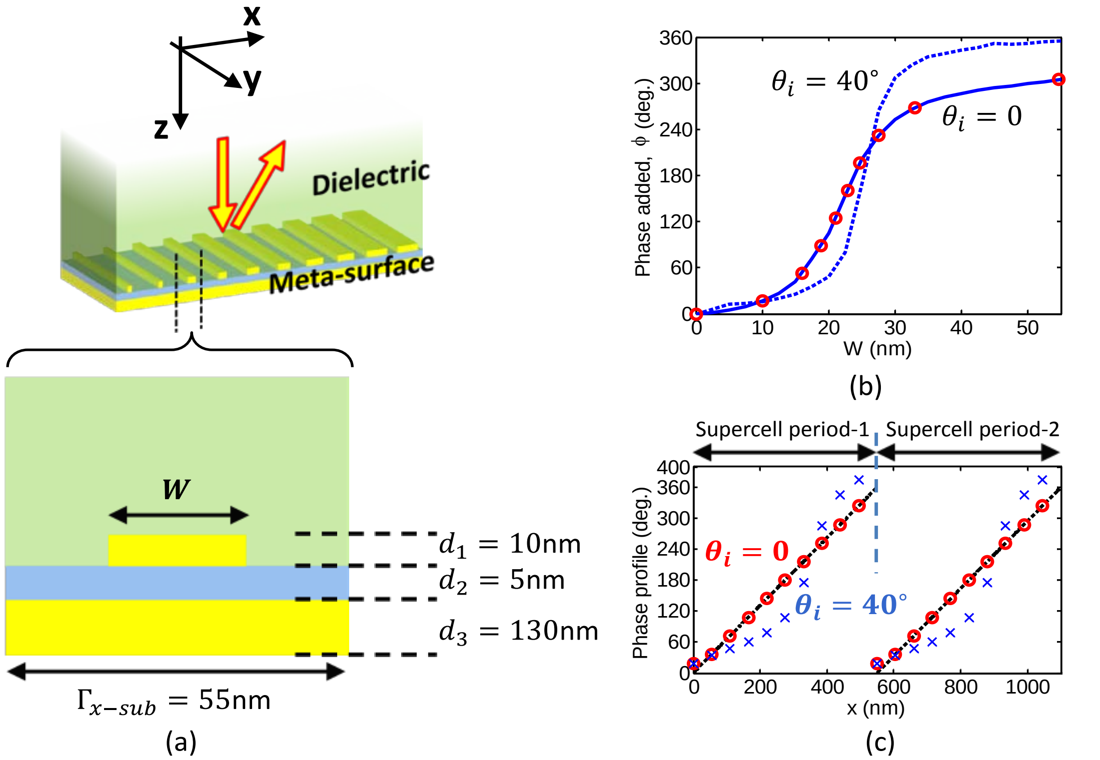
Simulated xylophone metasurface



Typical absorption in ultrathin layer (black) strong enhanced by metasurface (blue)

M. Ryyan Khan, Xufeng Wang, Peter Bermel, and Muhammad A. Alam, "Enhanced light trapping in solar cells with a meta-mirror following Generalized Snell's law," *Opt. Express* **22**, A973-A985 (2014).

Tailoring Metamirror Response for All Angles



W (nm)	0	10	16.05	18.88	21.09	22.84	24.74	27.56	33.04	55
Φ (deg.)	0	16.64	52.64	88.64	124.64	160.64	196.64	232.64	268.64	305.2

M. Ryyan Khan, Xufeng Wang, Peter Bermel, and Muhammad A. Alam, "Enhanced light trapping in solar cells with a meta-mirror following Generalized Snell's law," *Opt. Express* **22**, A973-A985 (2014).

Conclusions

- A wide range of surprising phenomena in nature, including mirages, opals, and negative refraction, can be understood through nanophotonics
- Further, these phenomena can be applied to improve light trapping in photovoltaics, photodetectors, and other applications
- Simulation tools available on nanoHUB including S4sim, QCRF-FDTD, and others can be leveraged to solve a broad range of problems