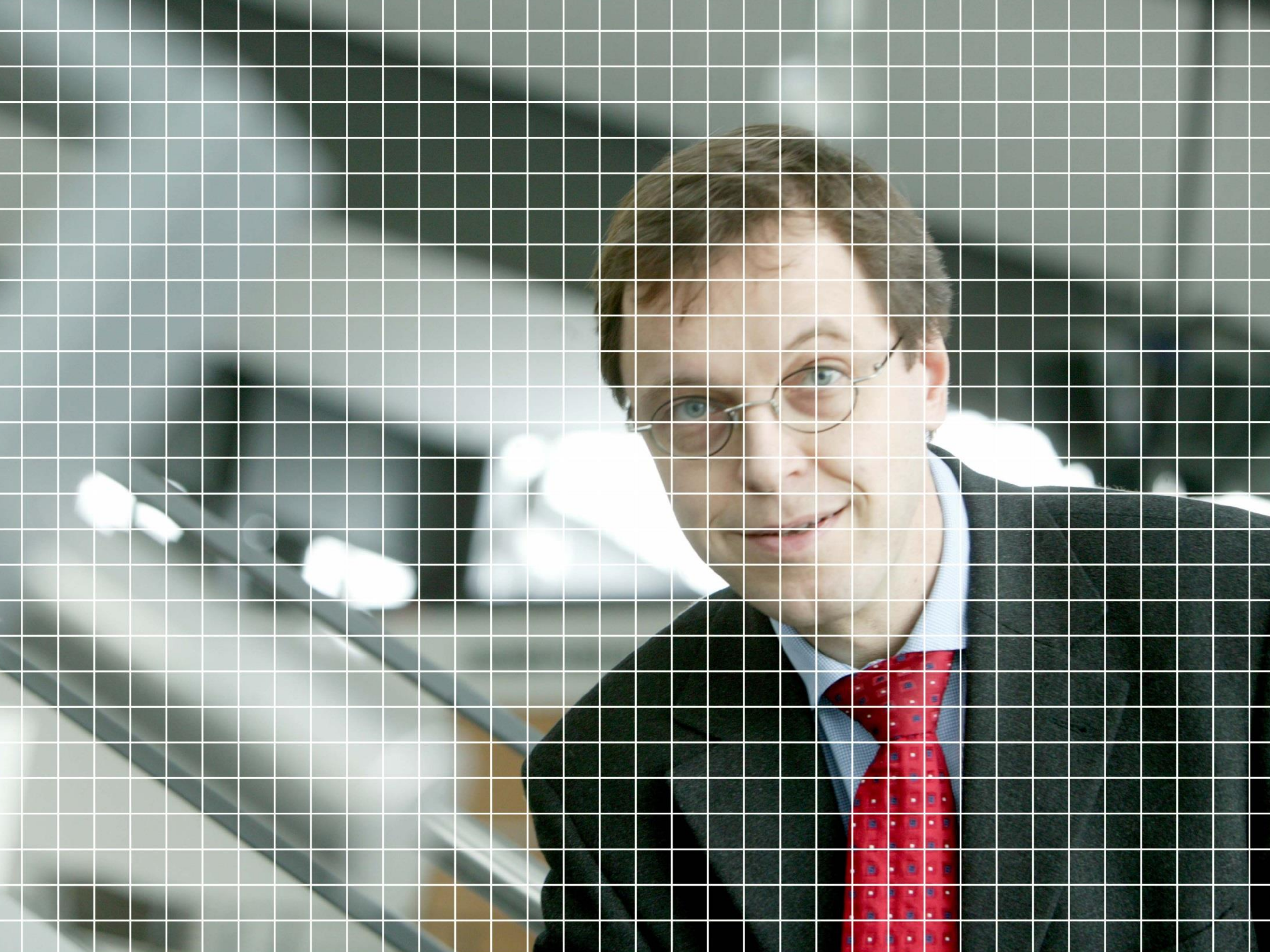
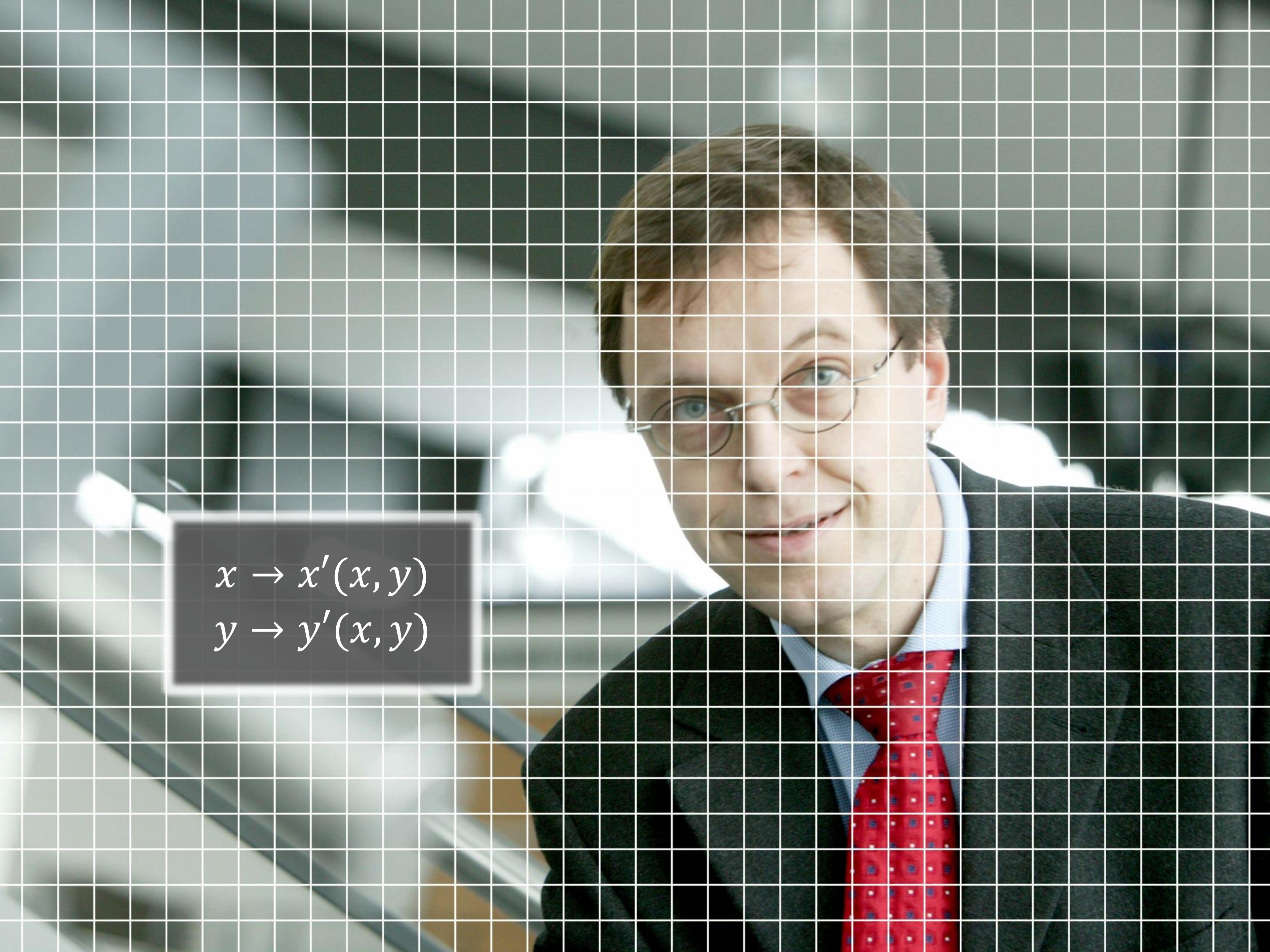
Invisibility Cloaking of Metal Contacts on Solar Cells and LEDs

Martin Wegener
Karlsruhe Institute of Technology (KIT), Germany

KIT, September 26, 2016




$x \to x'(x, y)$
$y \to y'(x, y)$


$x \to x'(x, y)$
$y \to y'(x, y)$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$y \to y'(x, y)$

Analytic solutions by transformation of boundaries

H. Lamb, "Hydromechanics", Cambridge University Press (1879)

D.Y. Lei et al., New J. Phys. 12, 093030 (2010)

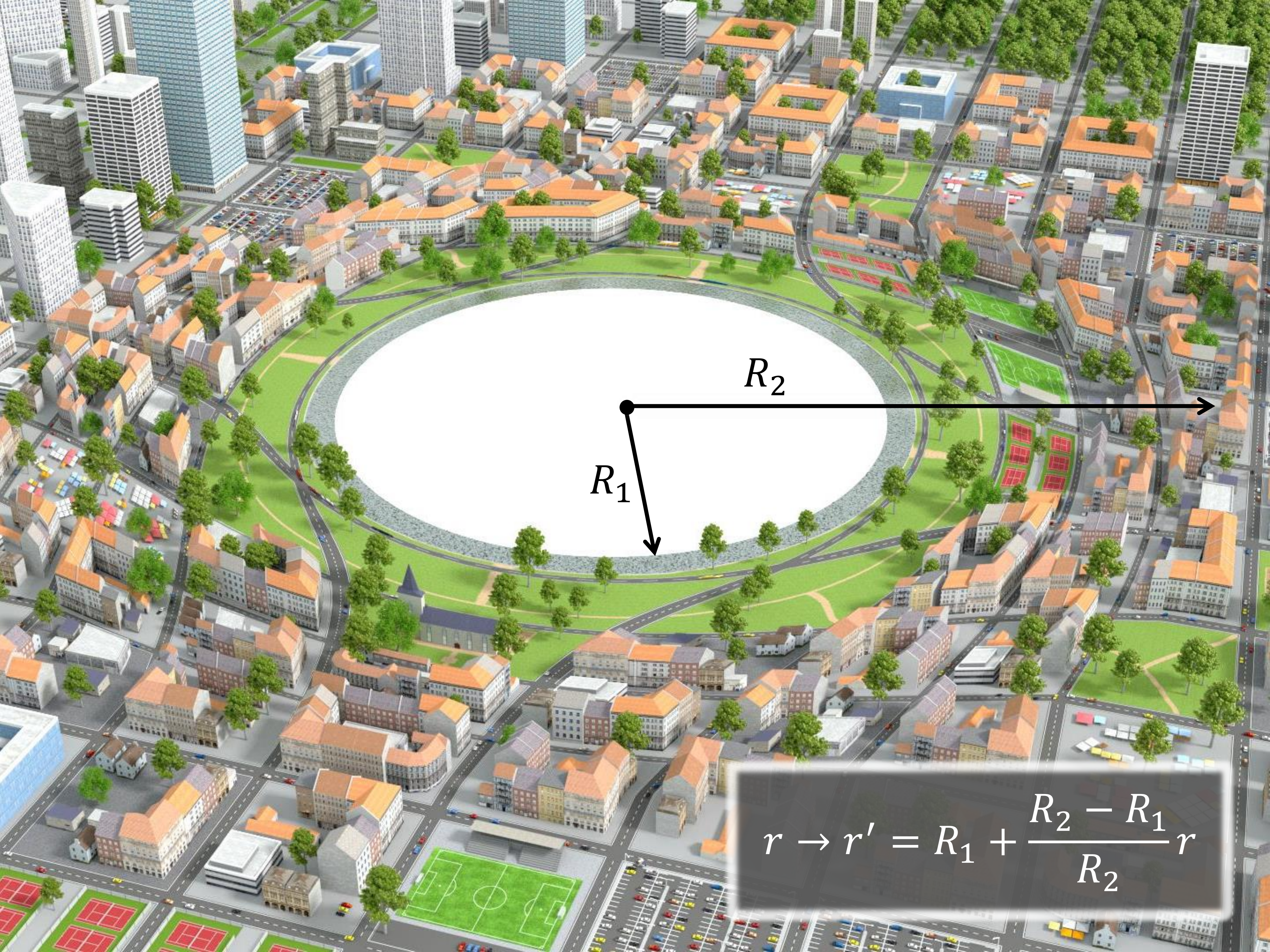
Design by transformation of material parameters

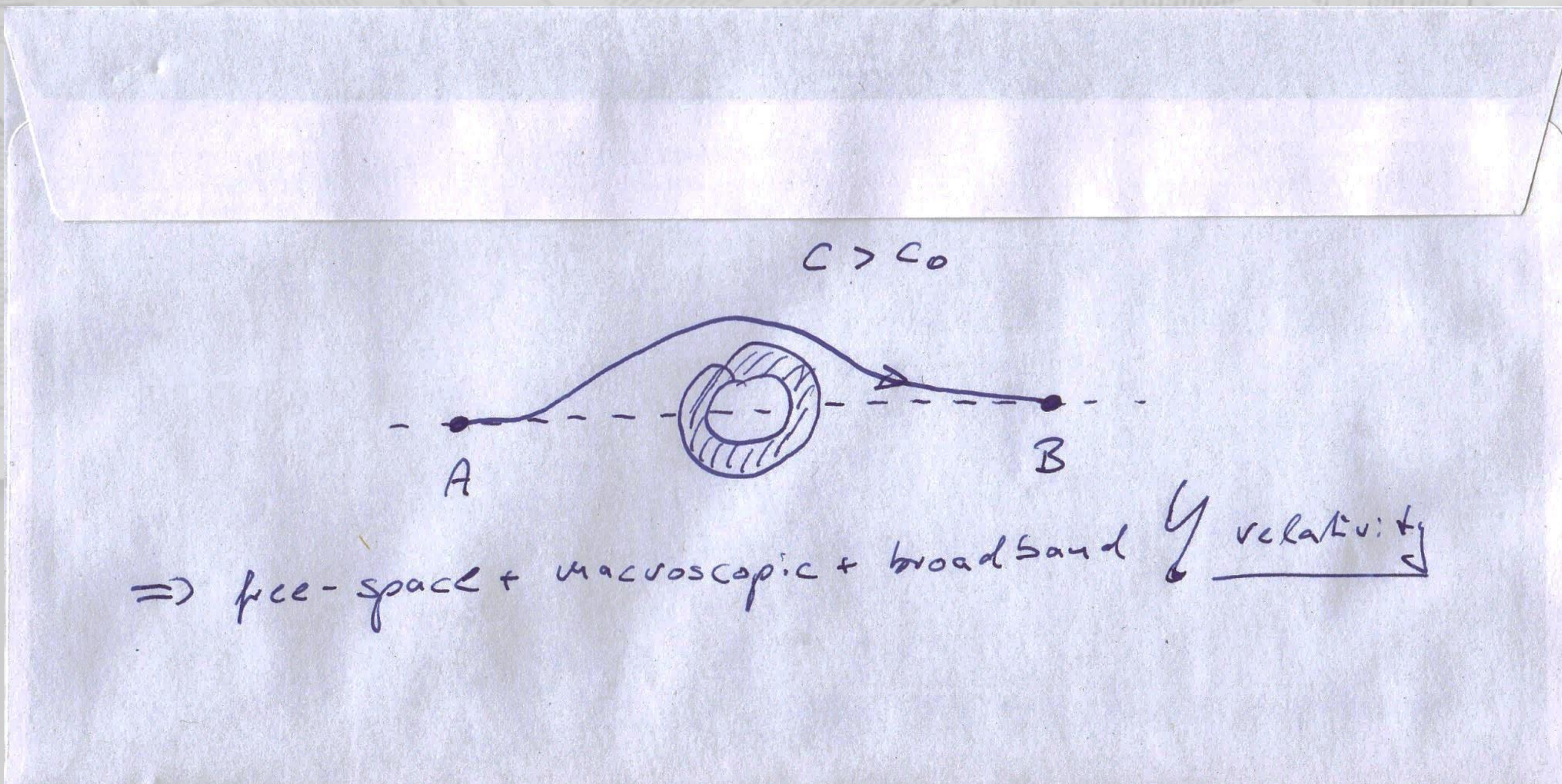
J.B. Pendry, D. Schurig, and D.R. Smith, Science 312, 1780 (2006)

U. Leonhardt, Science 312, 1777 (2006)

Design by transformation of surfaces

M. Schumann et al., Optica 2, 850 (2015)


R_2
R_1
$r \to r' = R_1 + \frac{R_2 - R_1}{R_2} r$



precisely, the size-bandwidth product is finite

electromagnetism	mechanics	thermodynamics
electrostatics	fluid mechanics	particle diffusion
$\vec{\nabla}\cdot\left(\epsilon\,\vec{\nabla}\phi\right)=0$	$\vec{\nabla}\cdot\left(\rho\,\vec{\nabla}\Phi\right)=0$	$\vec{\nabla}\cdot\left(D\,\vec{\nabla}n\right)=0$
magnetostatics	linear elasticity	heat conduction
$\vec{\nabla}\cdot\left(\mu\,\vec{\nabla}\varphi\right)=0$	$\vec{\nabla}\cdot\left(\overleftrightarrow{C}\,\vec{\nabla}\vec{u}\right)=0$	$\vec{\nabla}\cdot\left(\kappa\,\vec{\nabla}T\right)=0$
	Schrödinger eq.	electric conduction
	$\vec{\nabla}\cdot\left(m^{-1}\vec{\nabla}\psi\right)=0$	$\vec{\nabla}\cdot\left(\sigma\,\vec{\nabla}\phi\right)=0$

all from conservation laws; stationary case, locally isotropic media, E=0 in Schrödinger eq.

Performing a general 3D coordinate transformation

$$x_i \rightarrow x_i' = x_i'(x_1, x_2, x_3);\;\; i = 1, 2, 3$$

on

$$\vec{\nabla} \cdot \left(\epsilon\, \vec{\nabla}\phi\right) = 0$$

leads to a new material distribution via the Jacobian

$$\overleftrightarrow{\epsilon}' = \overleftrightarrow{J}\, \epsilon\, \overleftrightarrow{J}^{\mathrm{T}} \frac{1}{\det(\overleftrightarrow{J})}$$

$$\left(\overleftrightarrow{J}\right)_{ij} = \frac{\partial x_i'}{\partial x_j}$$

M. Kadic et al., Rep. Prog. Phys. 76, 126501 (2013)

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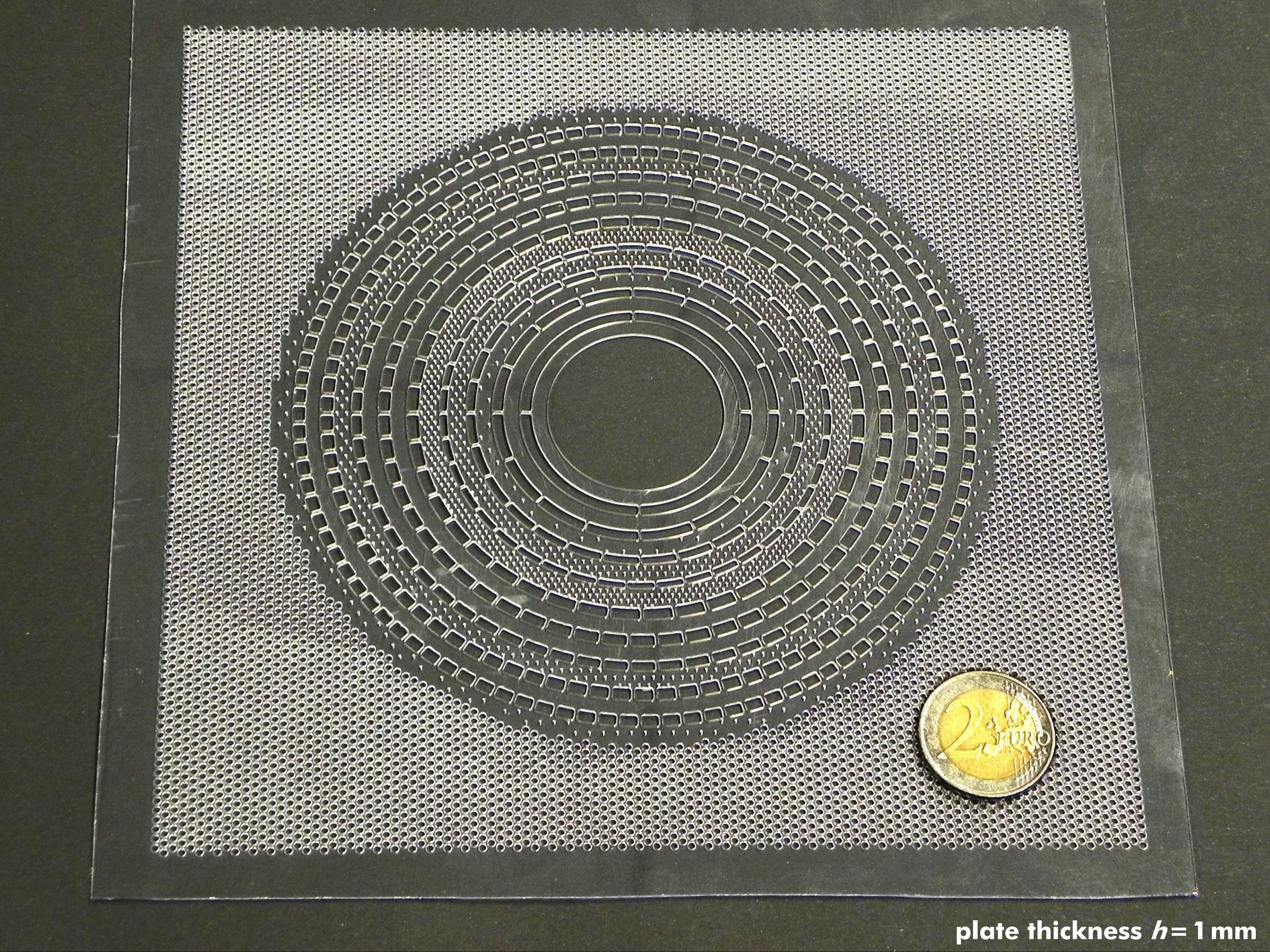
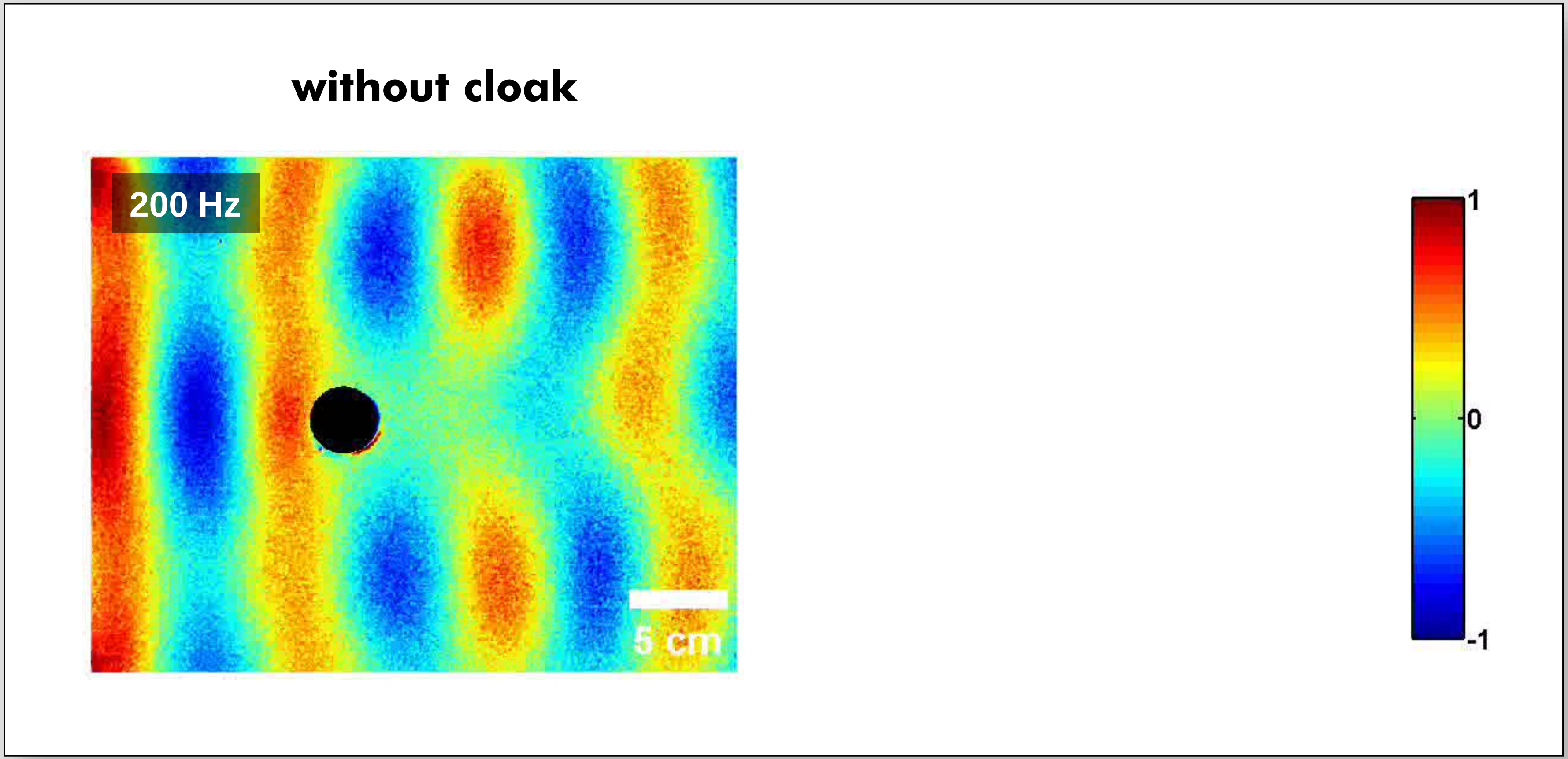


plate thickness $h = 1$ mm

Measured Movies



N. Stenger et al., Phys. Rev. Lett. 108, 014301 (2012)

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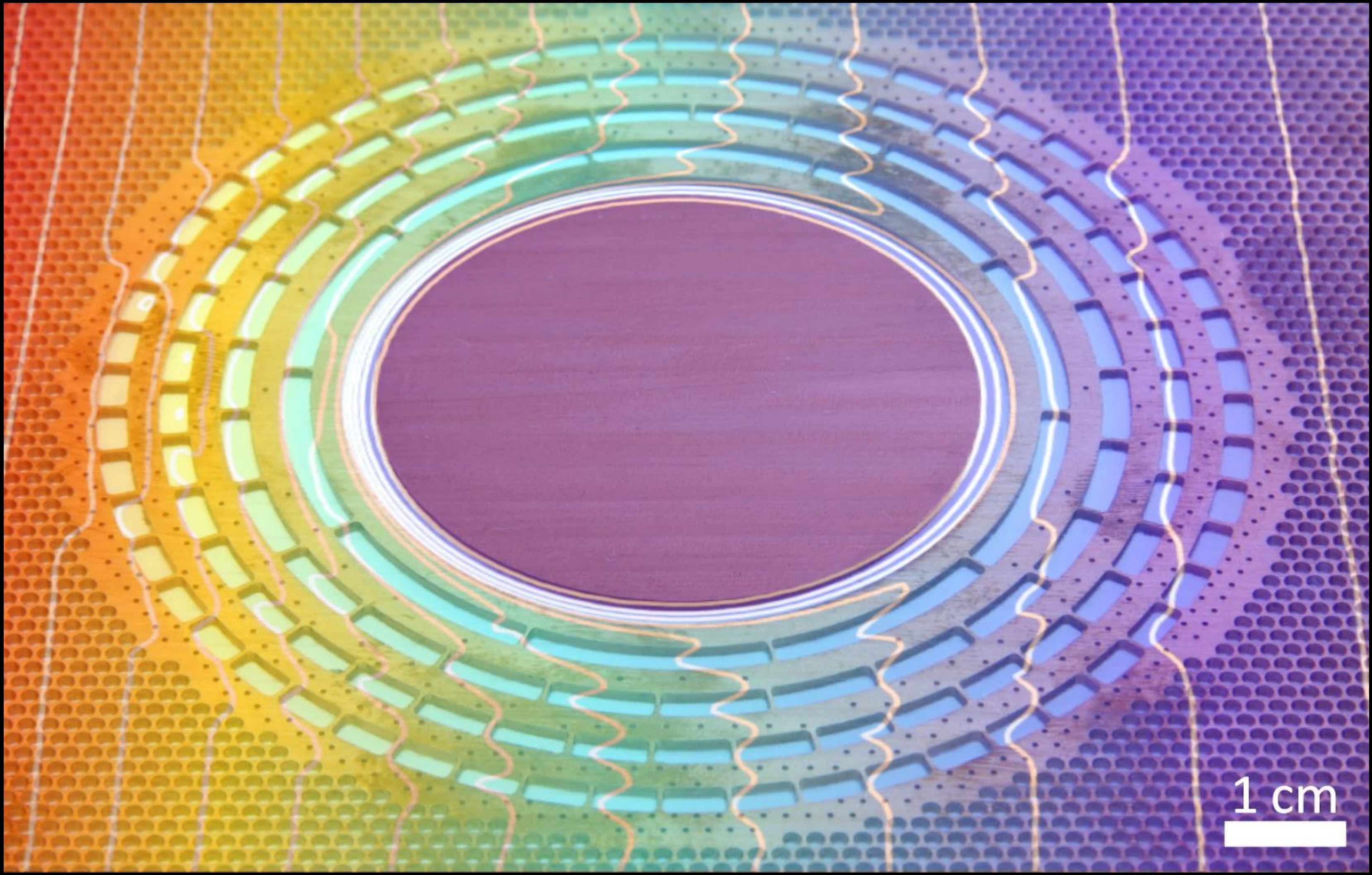
Thermal Cloaking



R. Schittny et al., Phys. Rev. Lett. 110, 195901 (2013)

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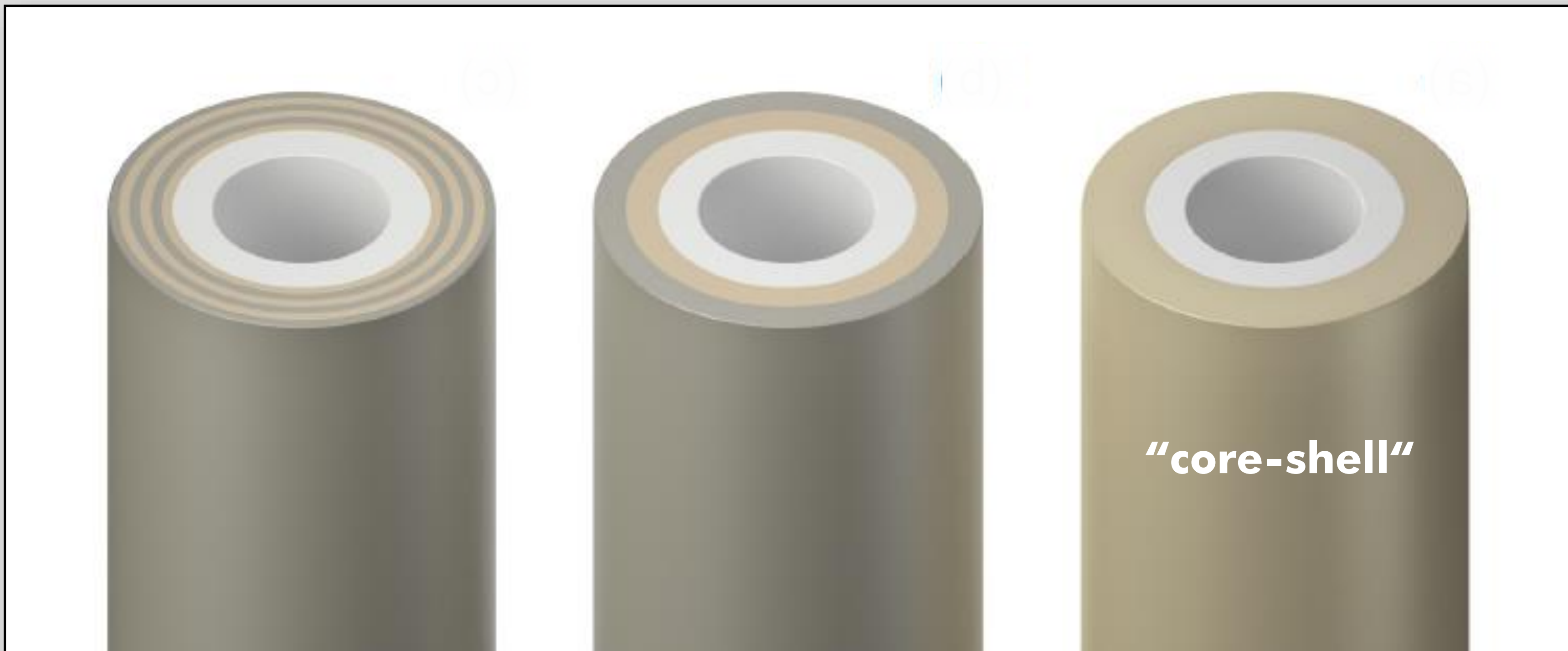
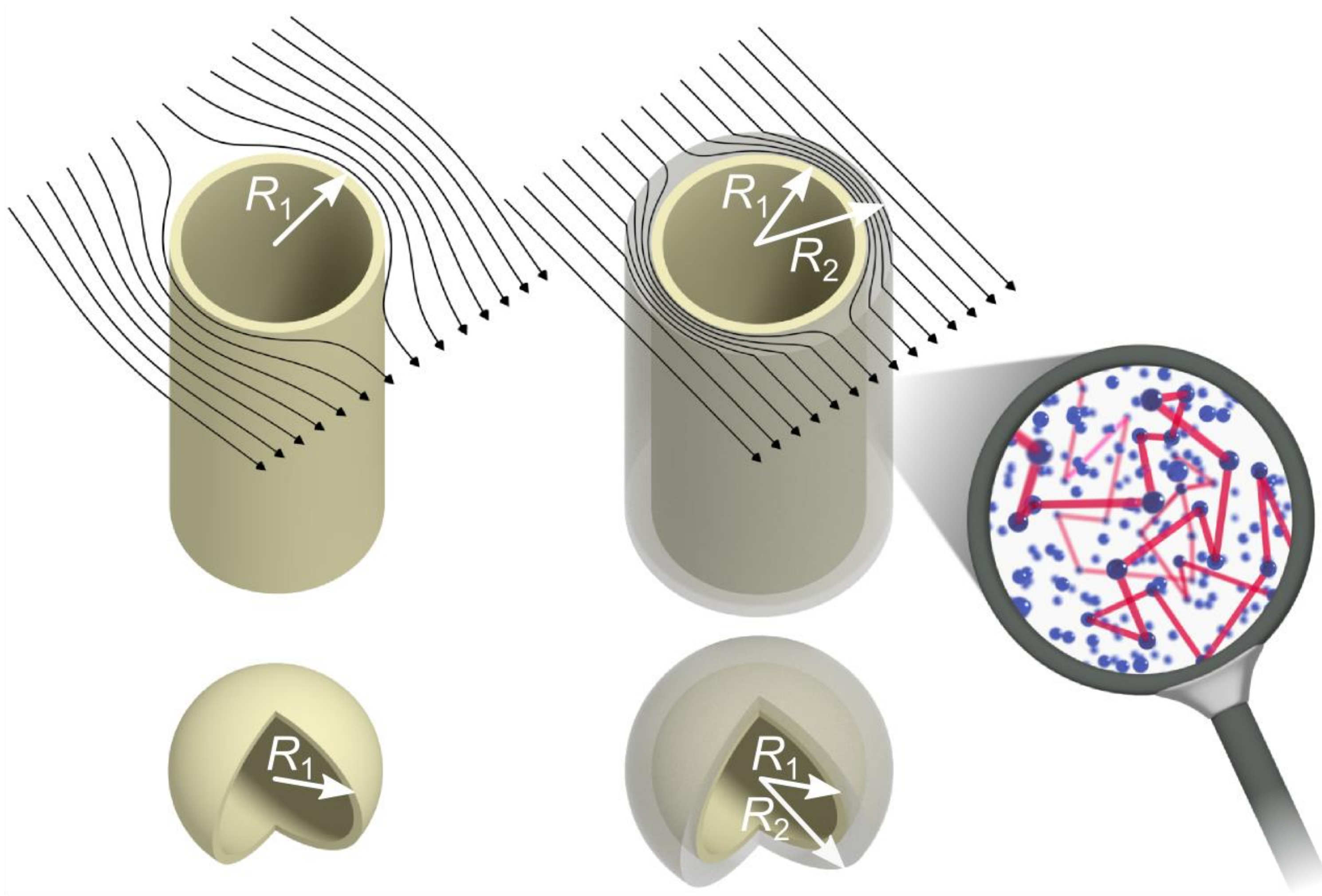
Diffusion of Light

Multiple Layers → Two Layers



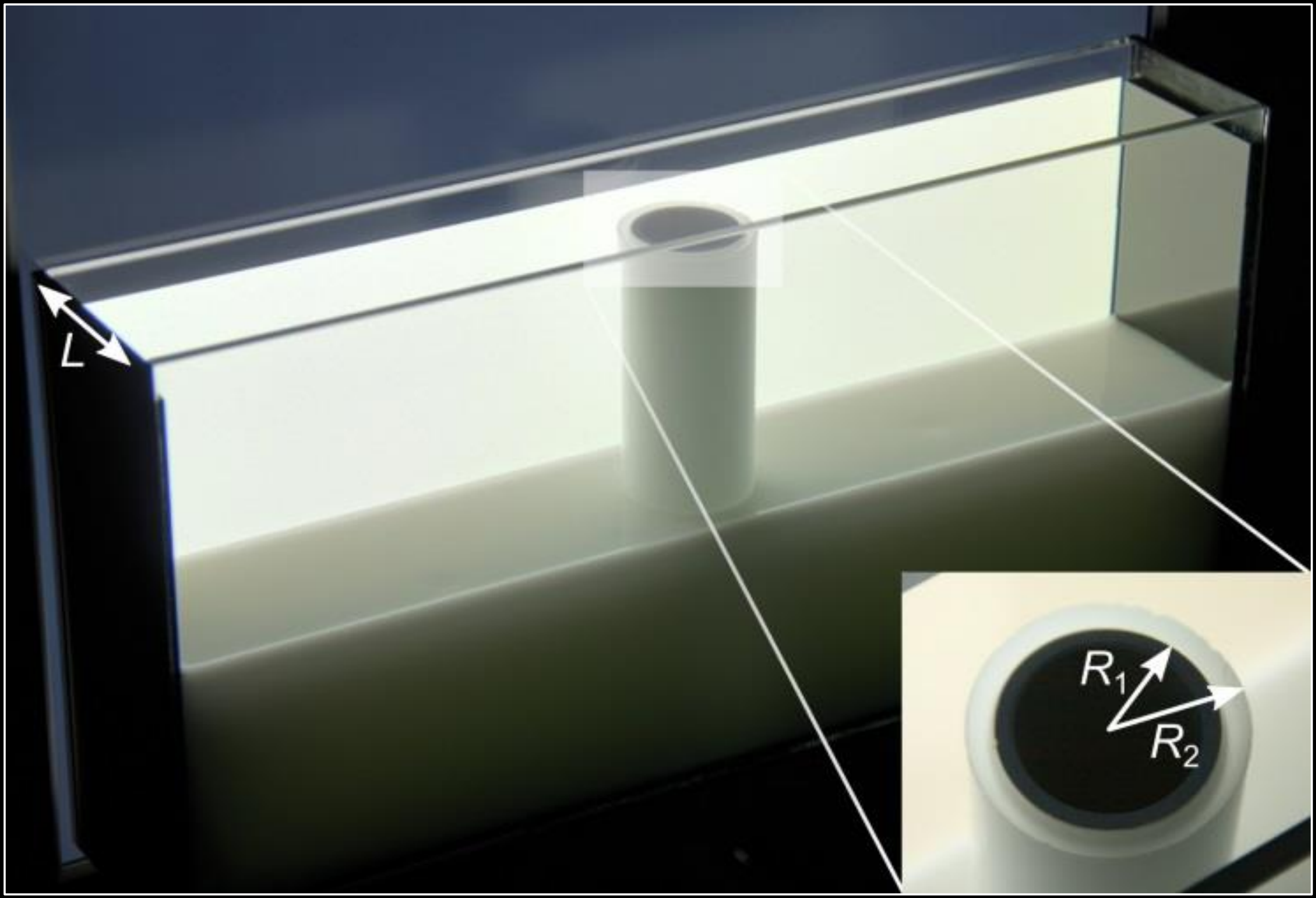
E.H. Kerner, Proc. Phys. Soc. B 69, 802 (1956)

Invisible for Diffuse Light

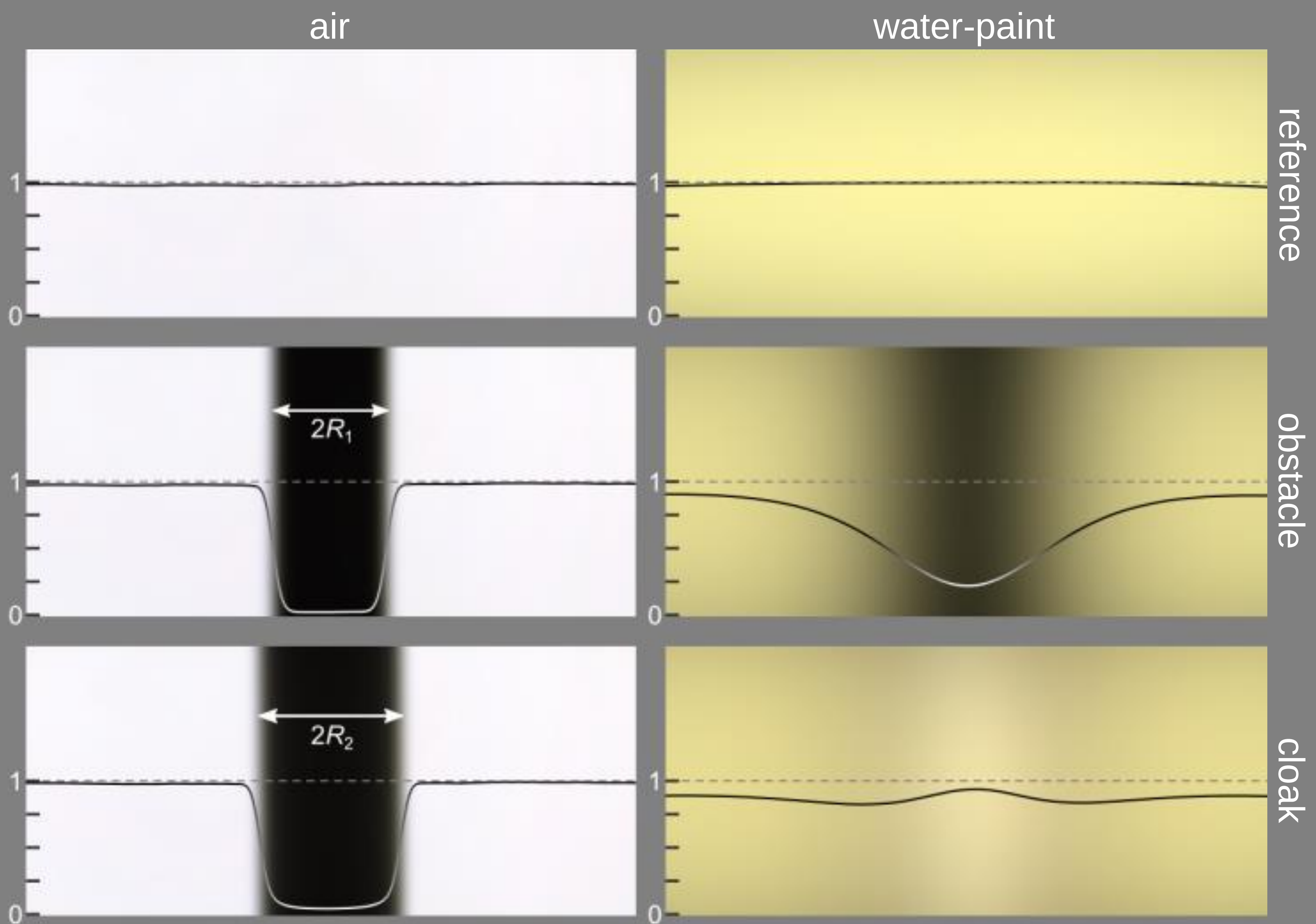


R. Schittny et al., Science 345, 427 (2014)

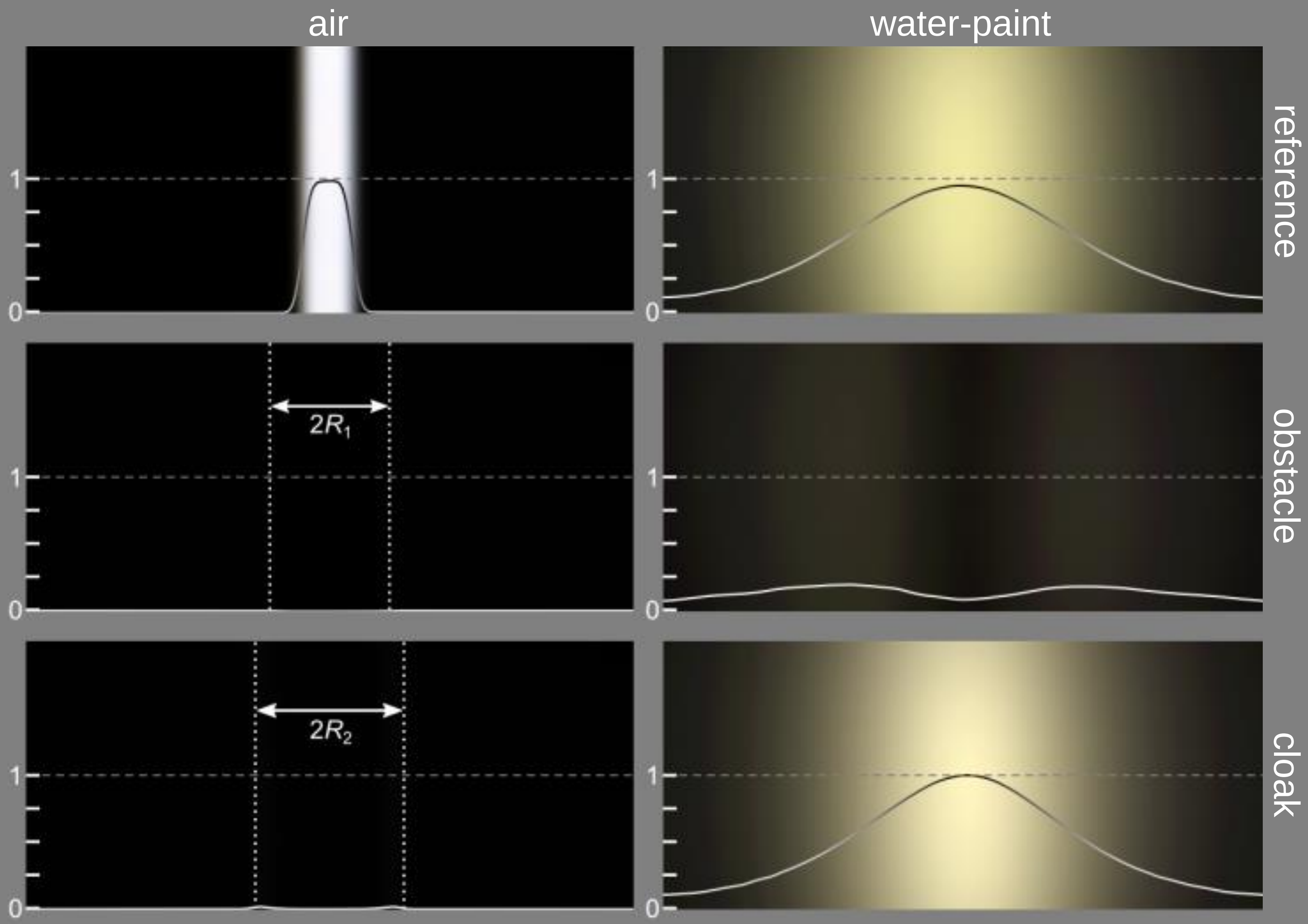
Experimental Setup

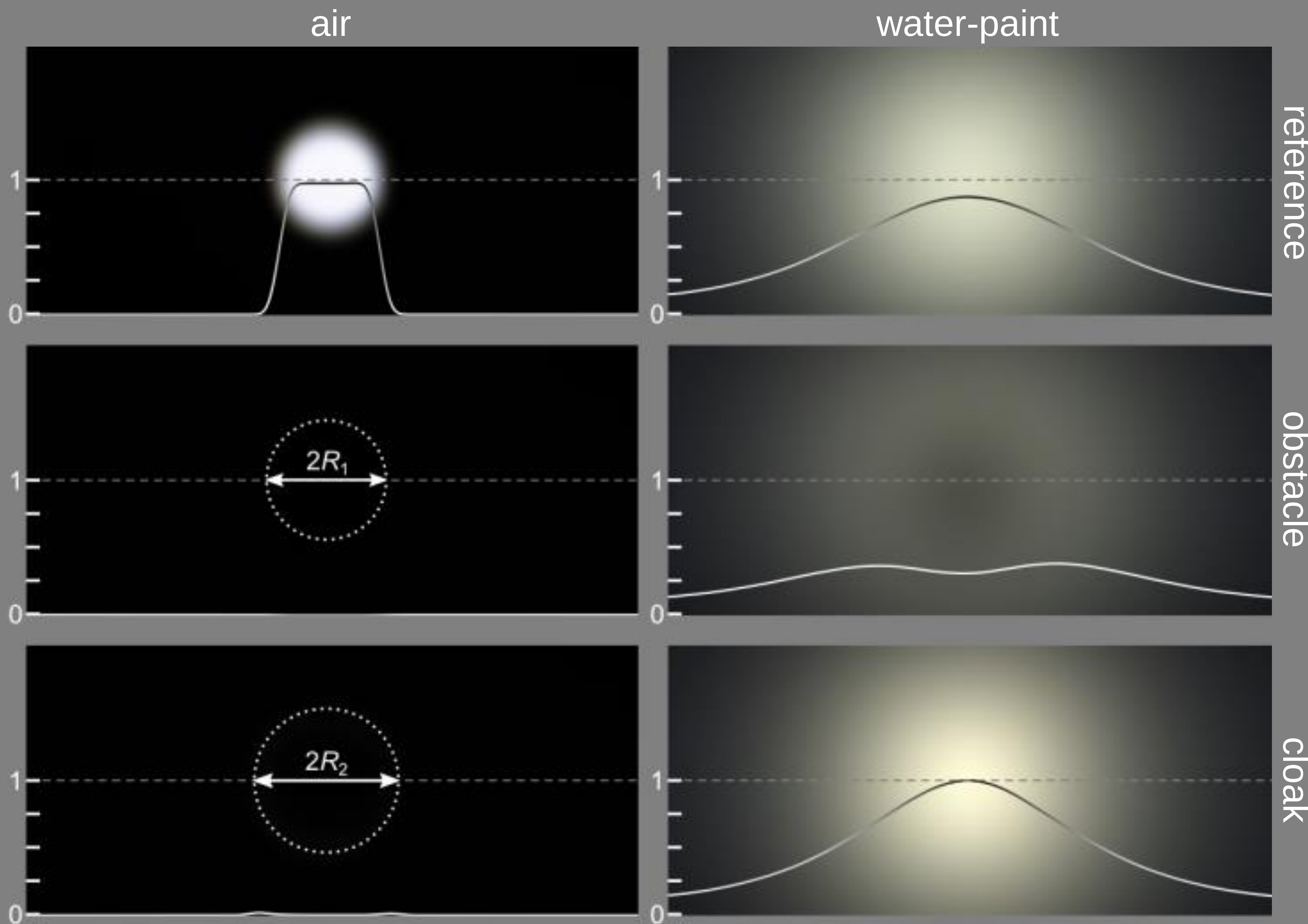


$L = 6.0\,\text{cm}$, $2R_1 = 3.2\,\text{cm}$, $2R_2 = 4.0\,\text{cm}$



air
water-paint
reference
obstacle
cloak
$2R_1$
$2R_2$
1
0


air
water-paint
reference
obstacle
cloak
2R1
2R2
1
0



air
water-paint
reference
obstacle
cloak
1
0
2R1
2R2

Application?

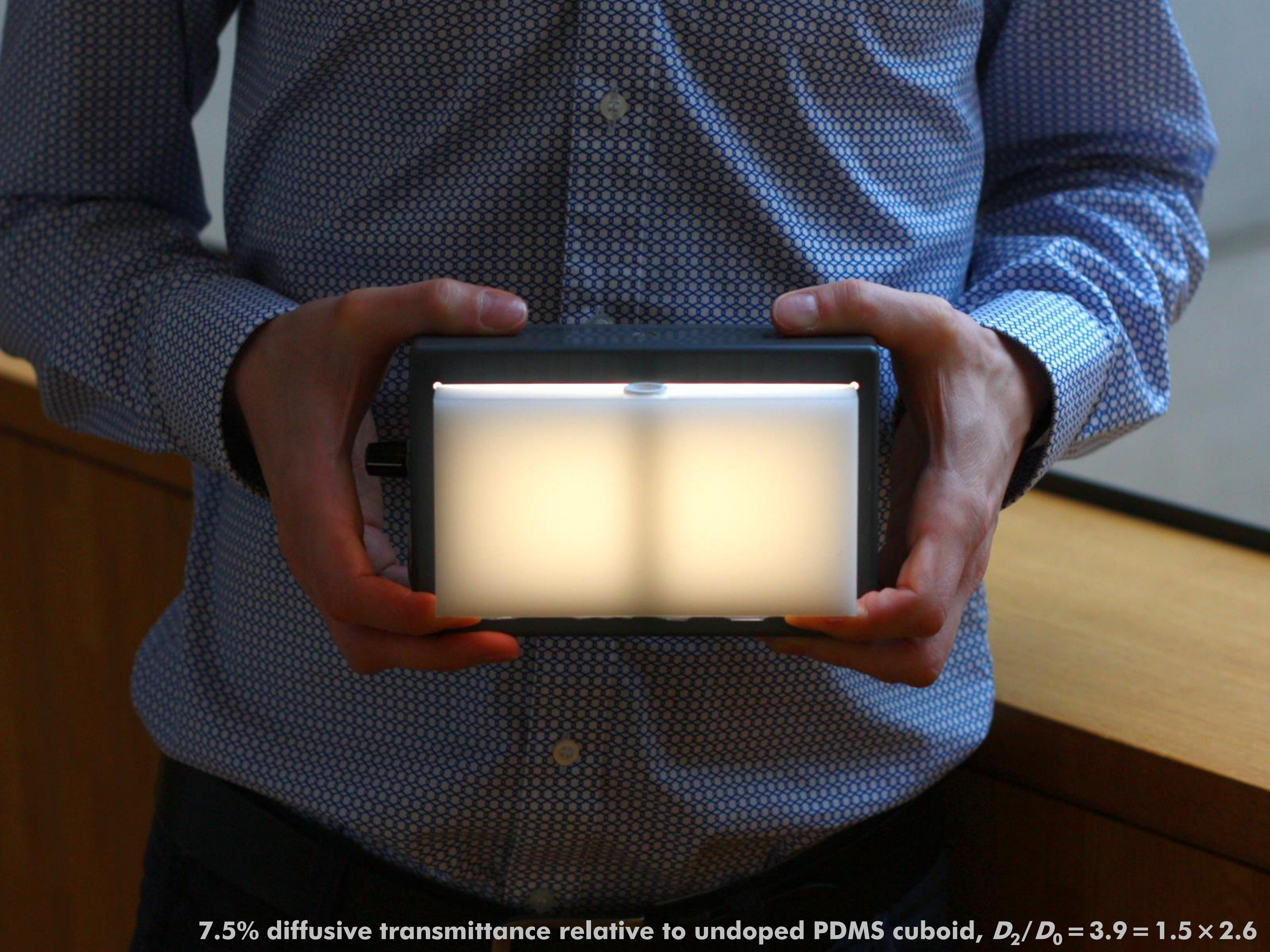
Recipe

1. Ceramic Accuflect® B6 [1] for core, @ $L = 3\,mm$: > 99% Lambertian diffusive reflectance for wavelengths > 650nm
2. Polydimethylsiloxan (PDMS) doped with high-quality TiO_2 nanoparticles [2] for shell and surrounding, 125nm radius
3. To reduce doping concentrations, hence increase transmittance, use $R_2/R_1 = 1.5$

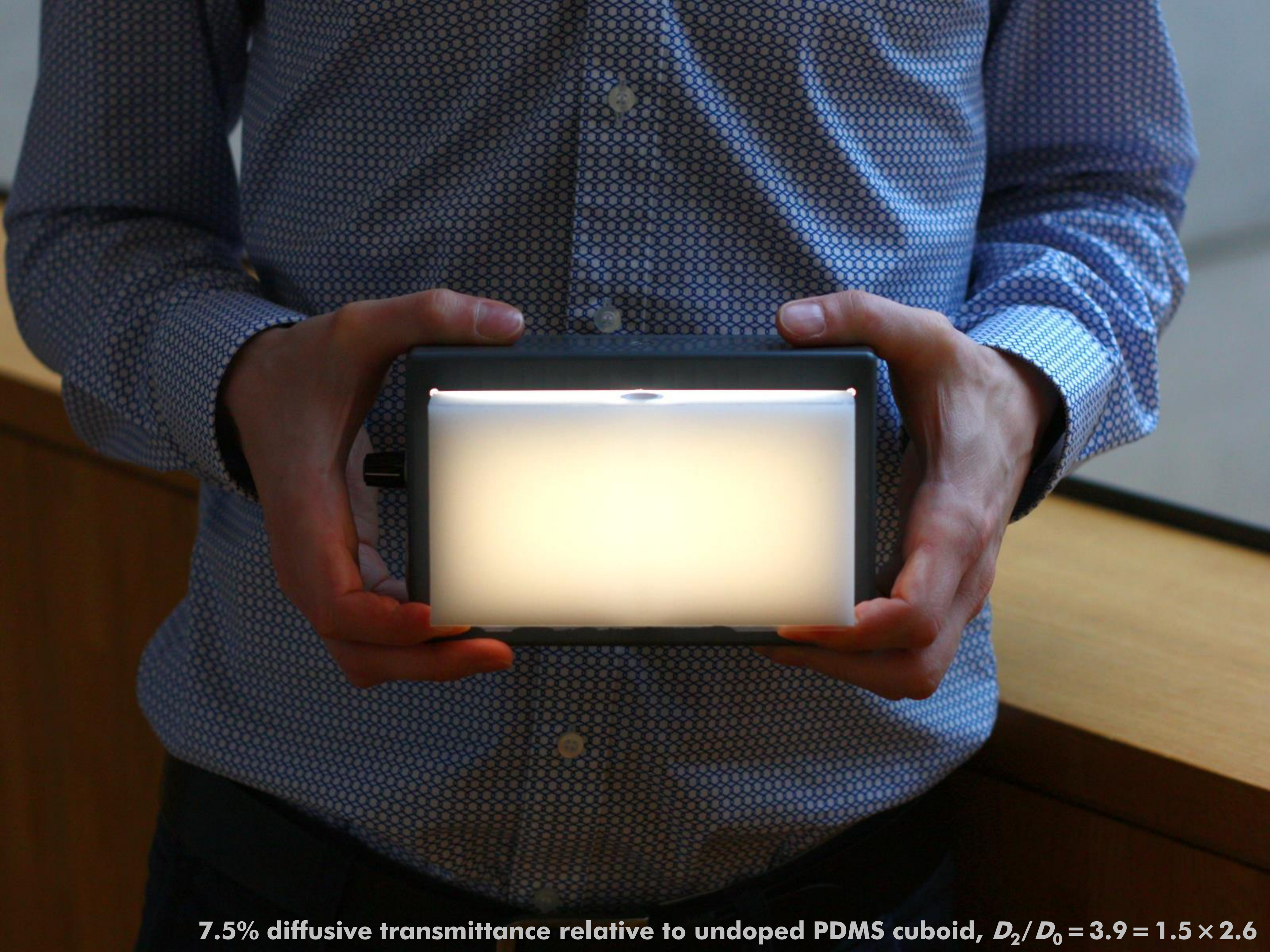
[1] Accuratus Corporation (USA); [2] DuPont R700 (Germany), thanks to Georg Maret's group

Samples

$L_x = 15\,\text{cm}$, $L_y = 8\,\text{cm}$, $L_z = 3\,\text{cm}$, $R_1 = 0.8\,\text{cm}$, $R_2 = 1.2\,\text{cm}$



7.5% diffusive transmittance relative to undoped PDMS cuboid, $D_2/D_0 = 3.9 = 1.5 \times 2.6$



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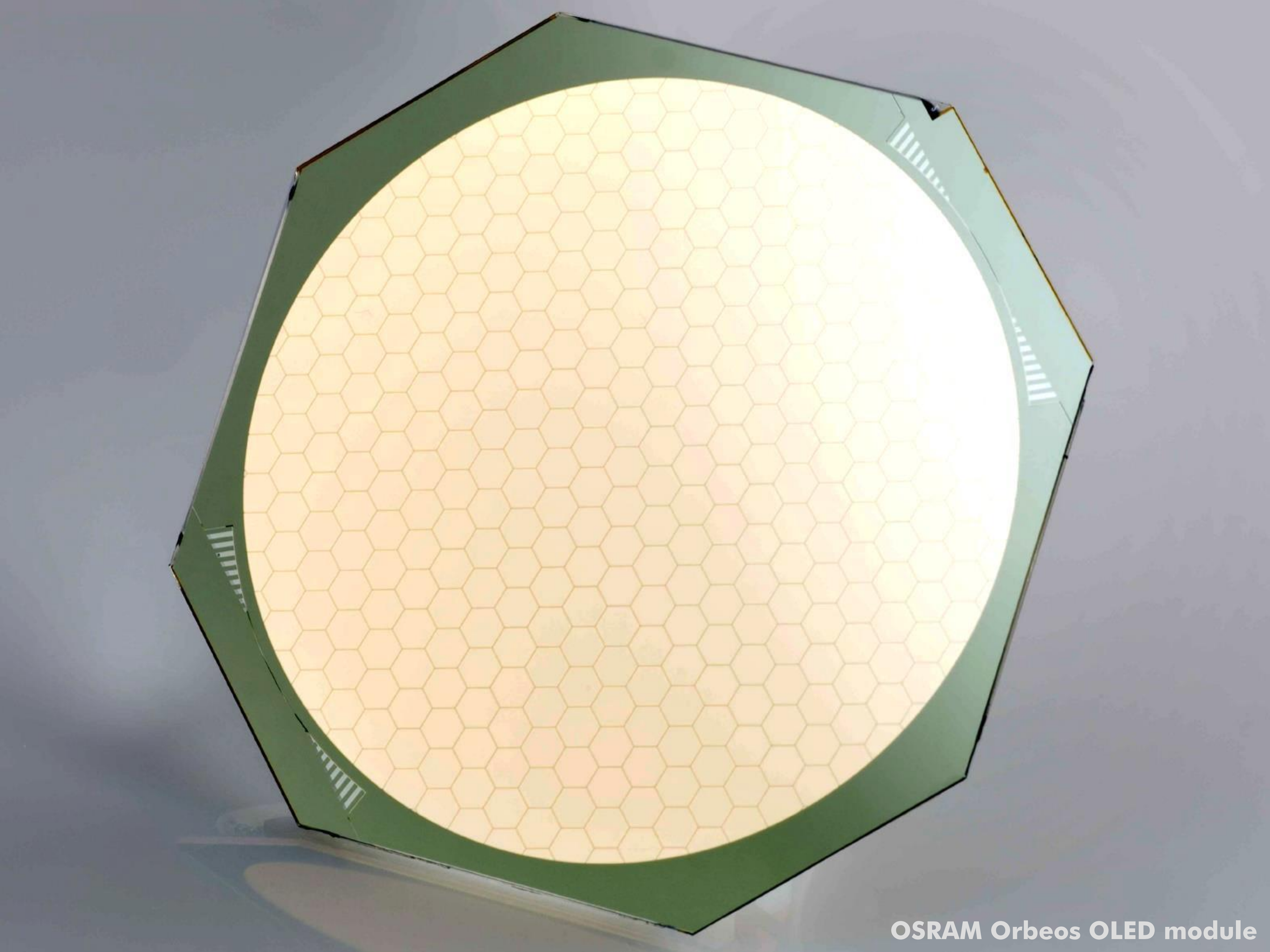
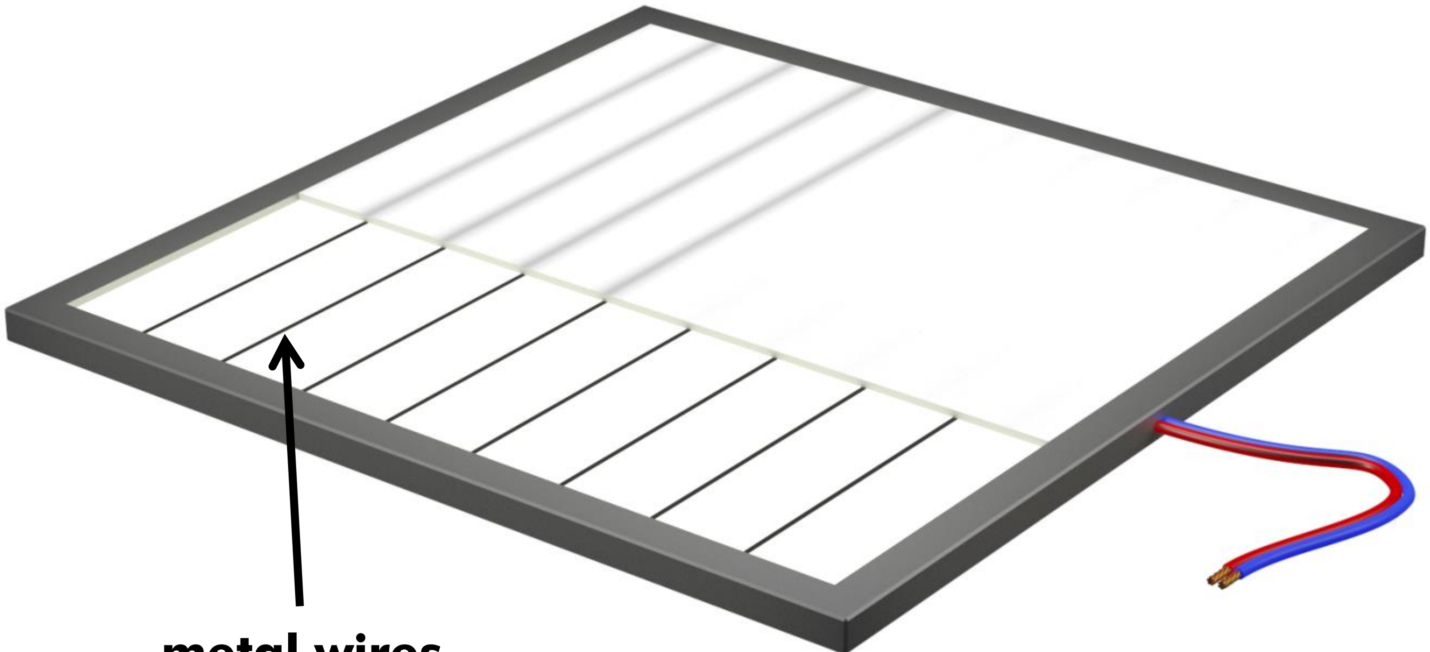
R. Schittny et al., Opt. Lett. 40, 4202 (2015)

Application?



OSRAM Orbeos OLED module

OLED Wallpaper



F. Mayer et al., Adv. Opt. Mater. 4, 740 (2016)

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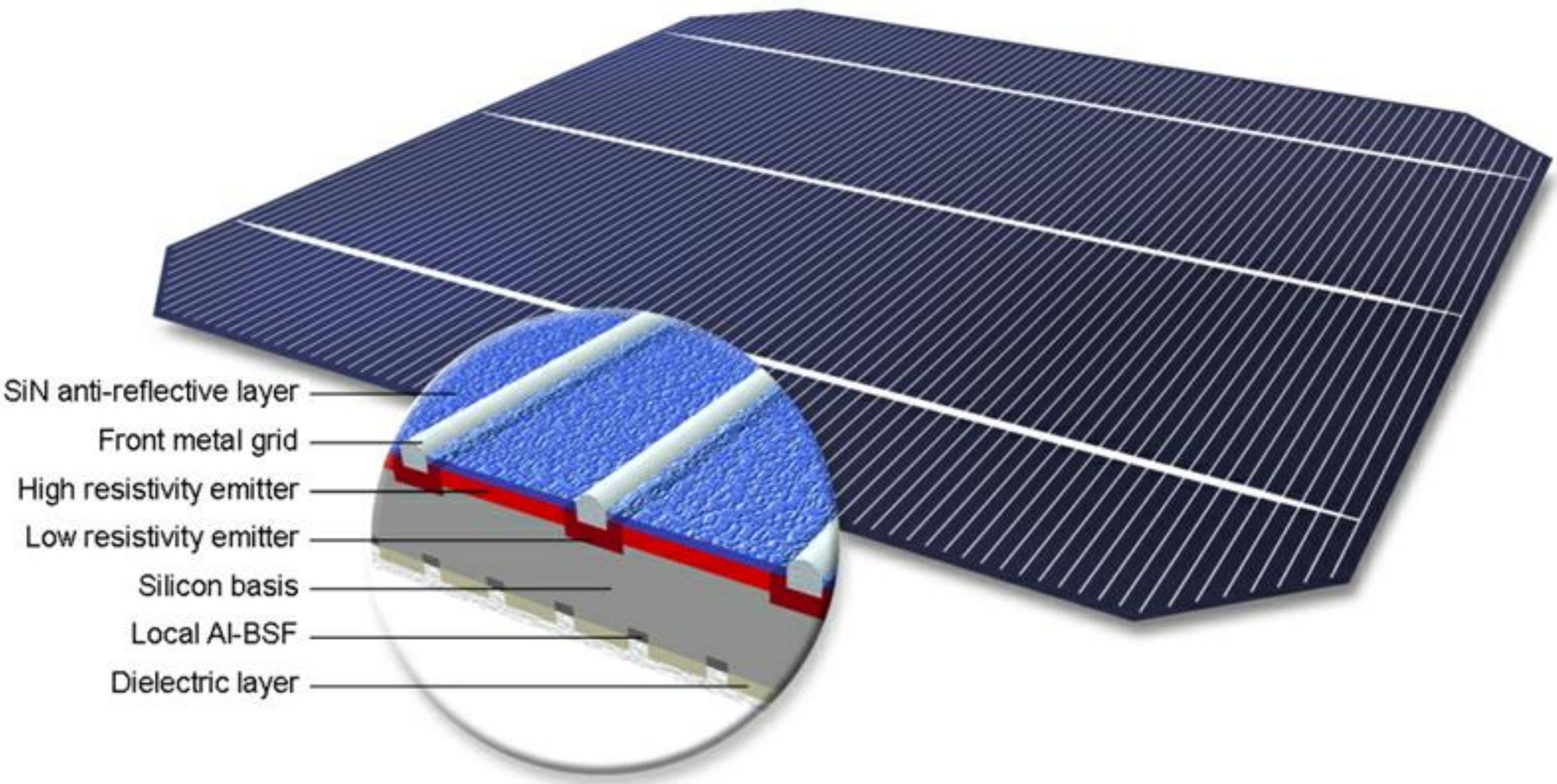
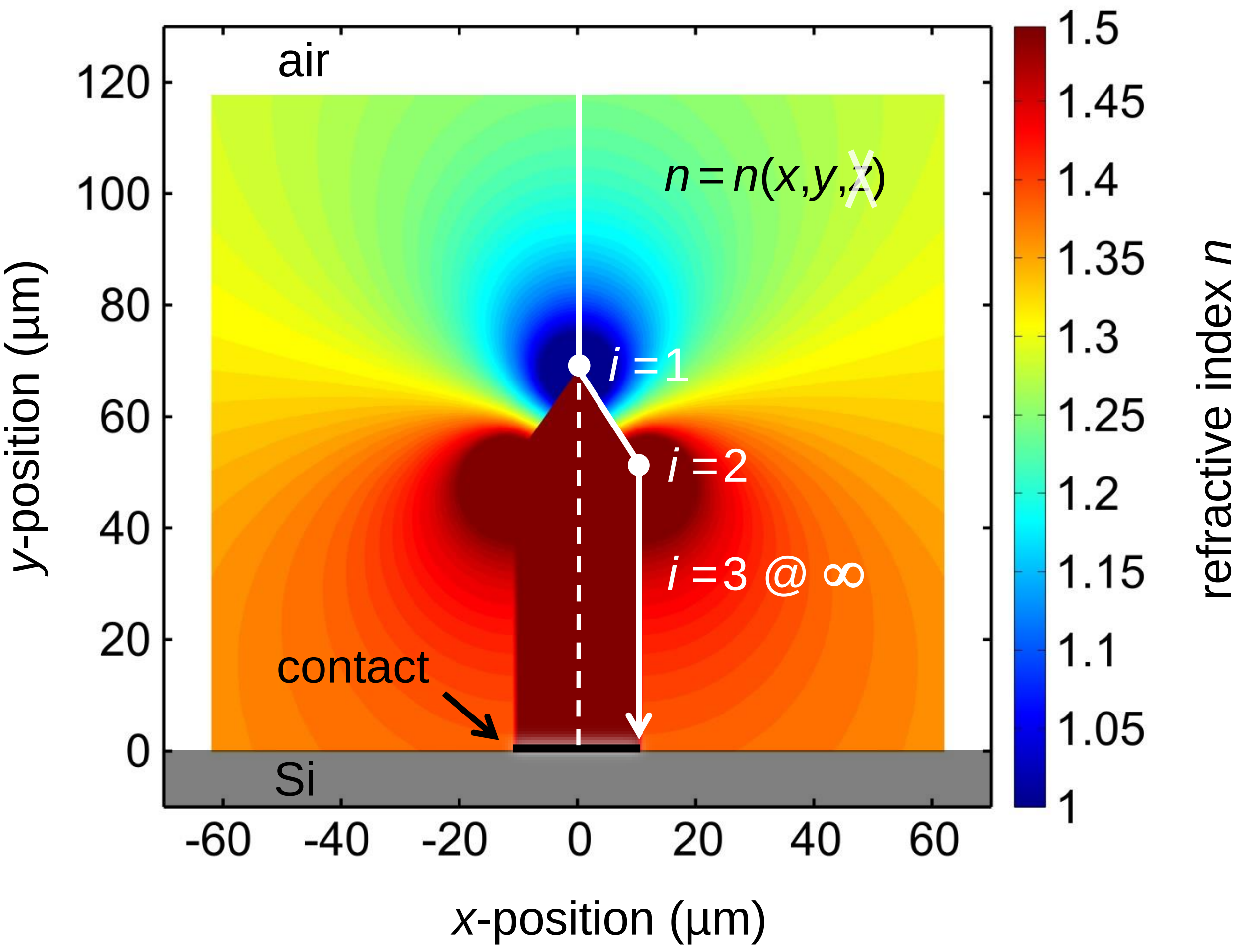
Invisible Contacts?



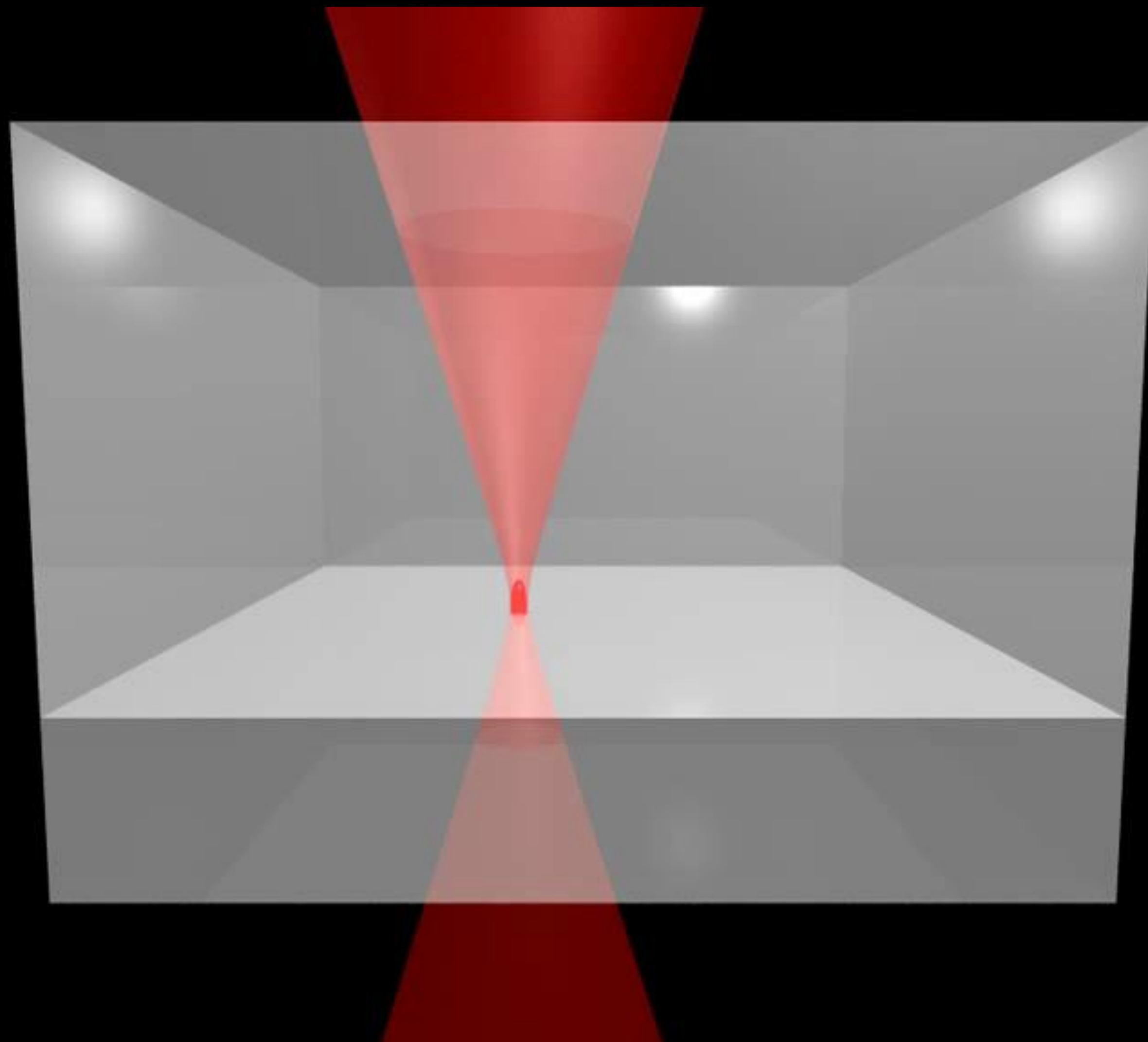
SITEC GmbH, centrotherm website; J.C. Halimeh et al., Opt. Express 21, 9457 (2013)

Invisible Contacts



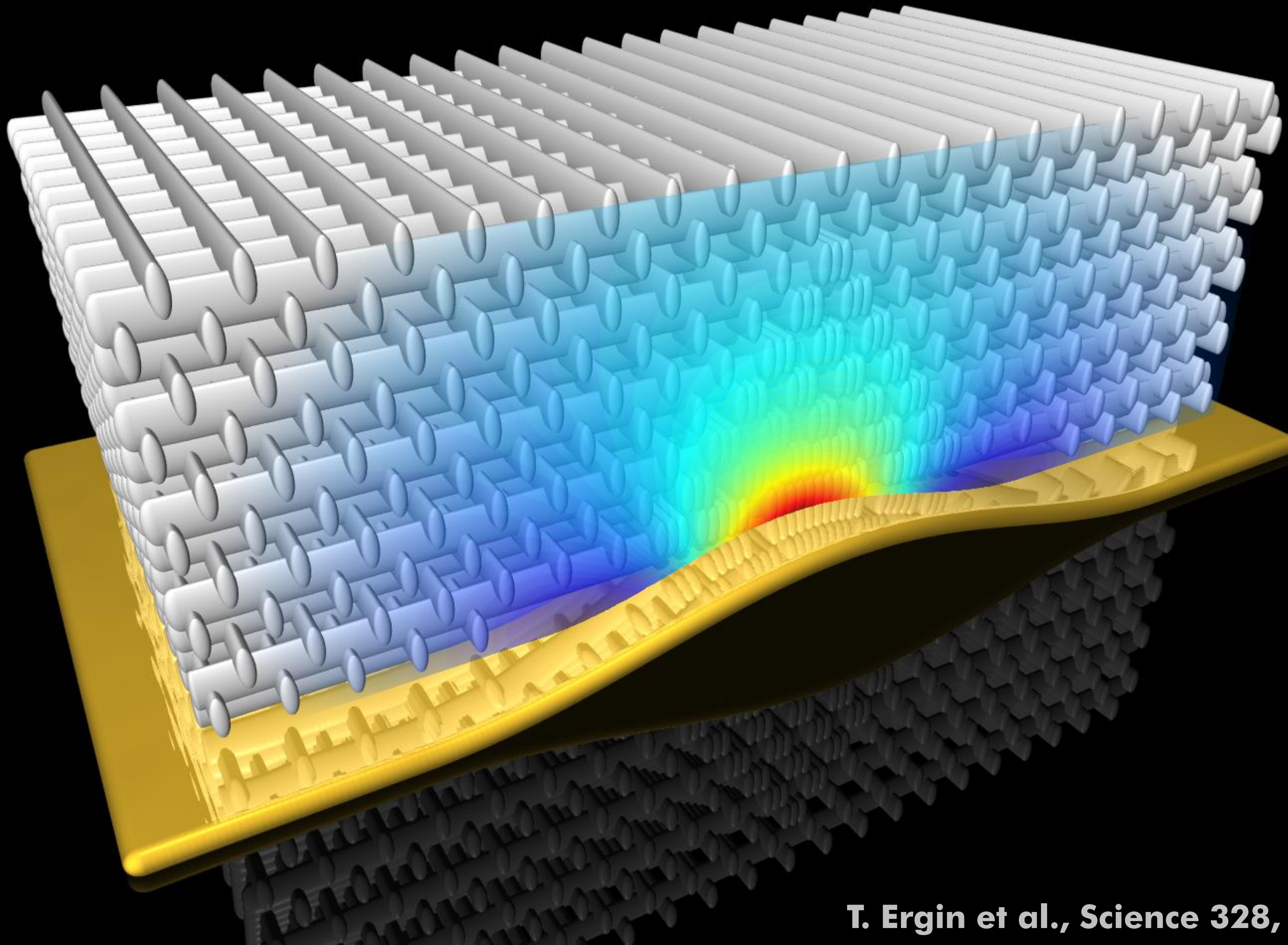
M. Schumann et al., Optica 2, 850 (2015)

3D Laser Lithography



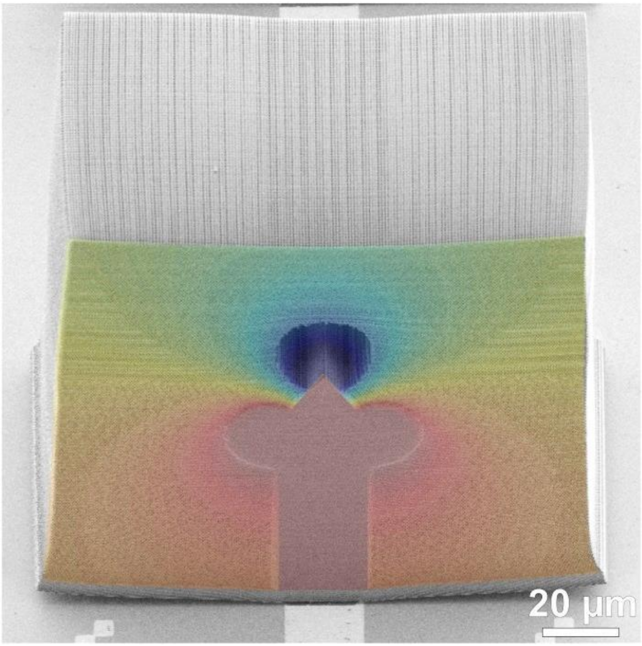
scheme not to scale, actual NA = 1.4, Tolga Ergin

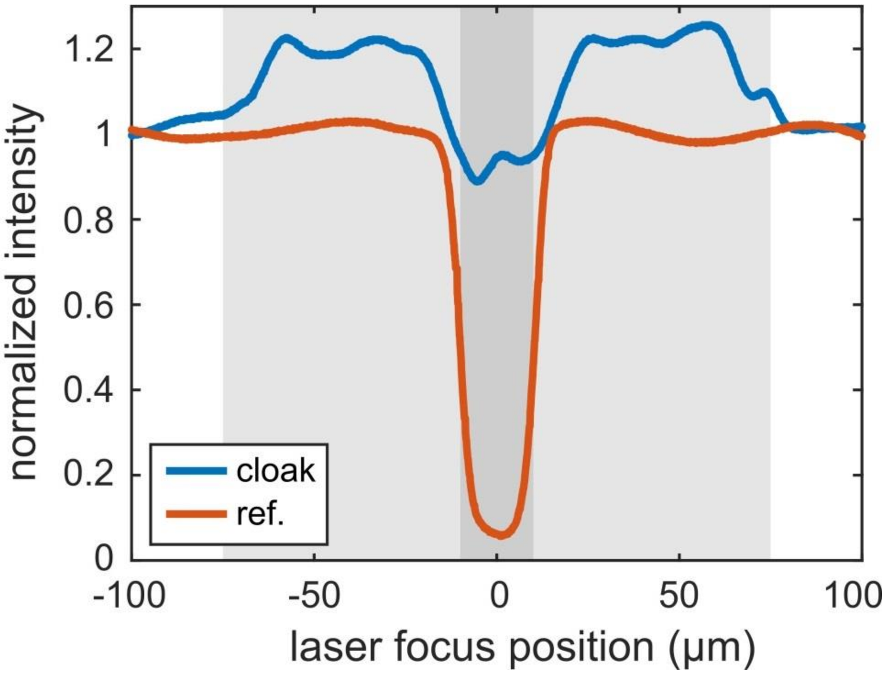
3D Carpet Cloak



T. Ergin et al., Science 328, 337 (2010)

Experimental Results



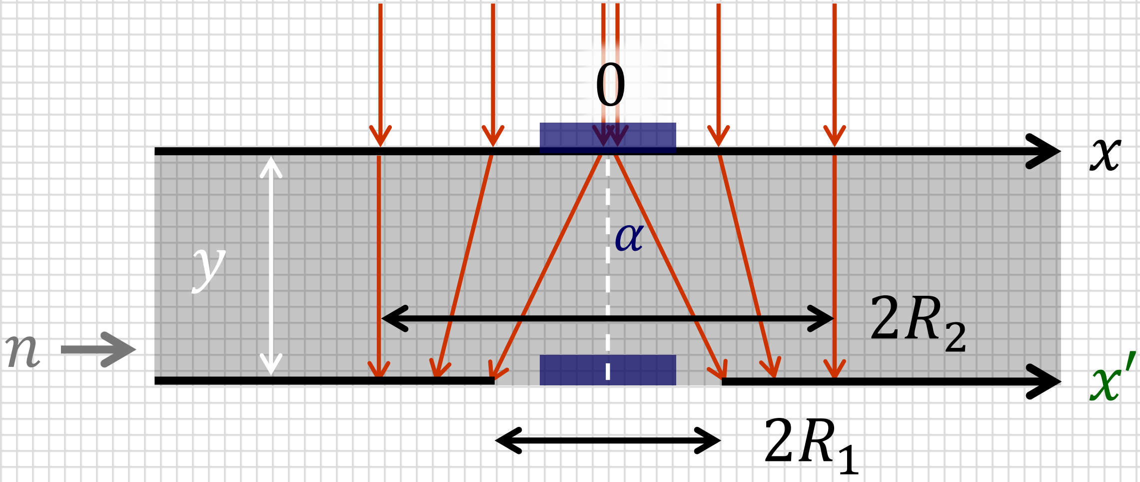


429 woodpile layers, $a = 0.8\mu m$ rod spacing, $\lambda = 1.6\mu m$ wavelength

Transformed Surfaces

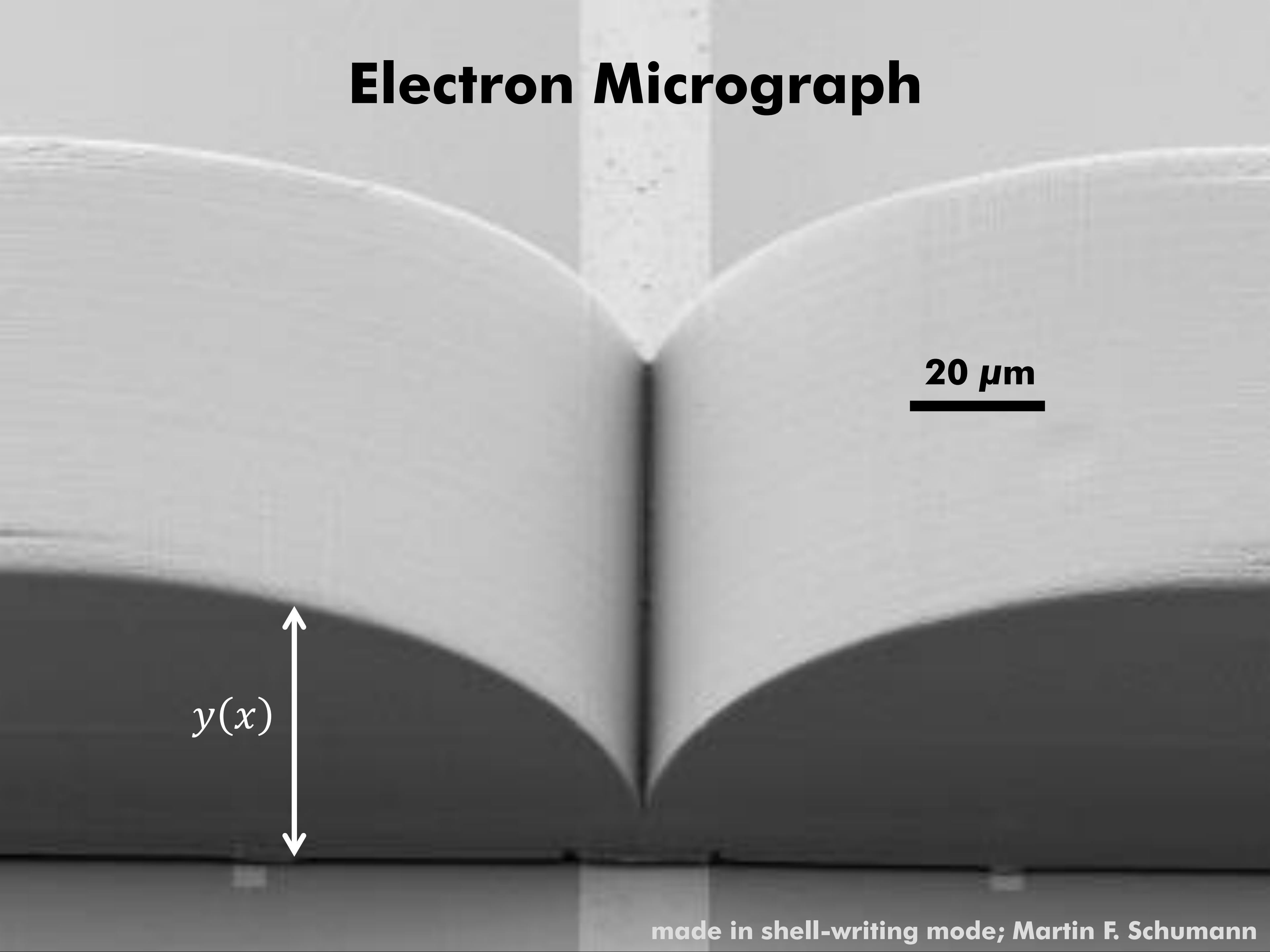
For **normal incidence** **of rays, a region of width $2R_1$ can be avoided using the** **1D transformation**

$$x \rightarrow x' = R_1 + \frac{R_2 - R_1}{R_2} x; \quad x > 0$$

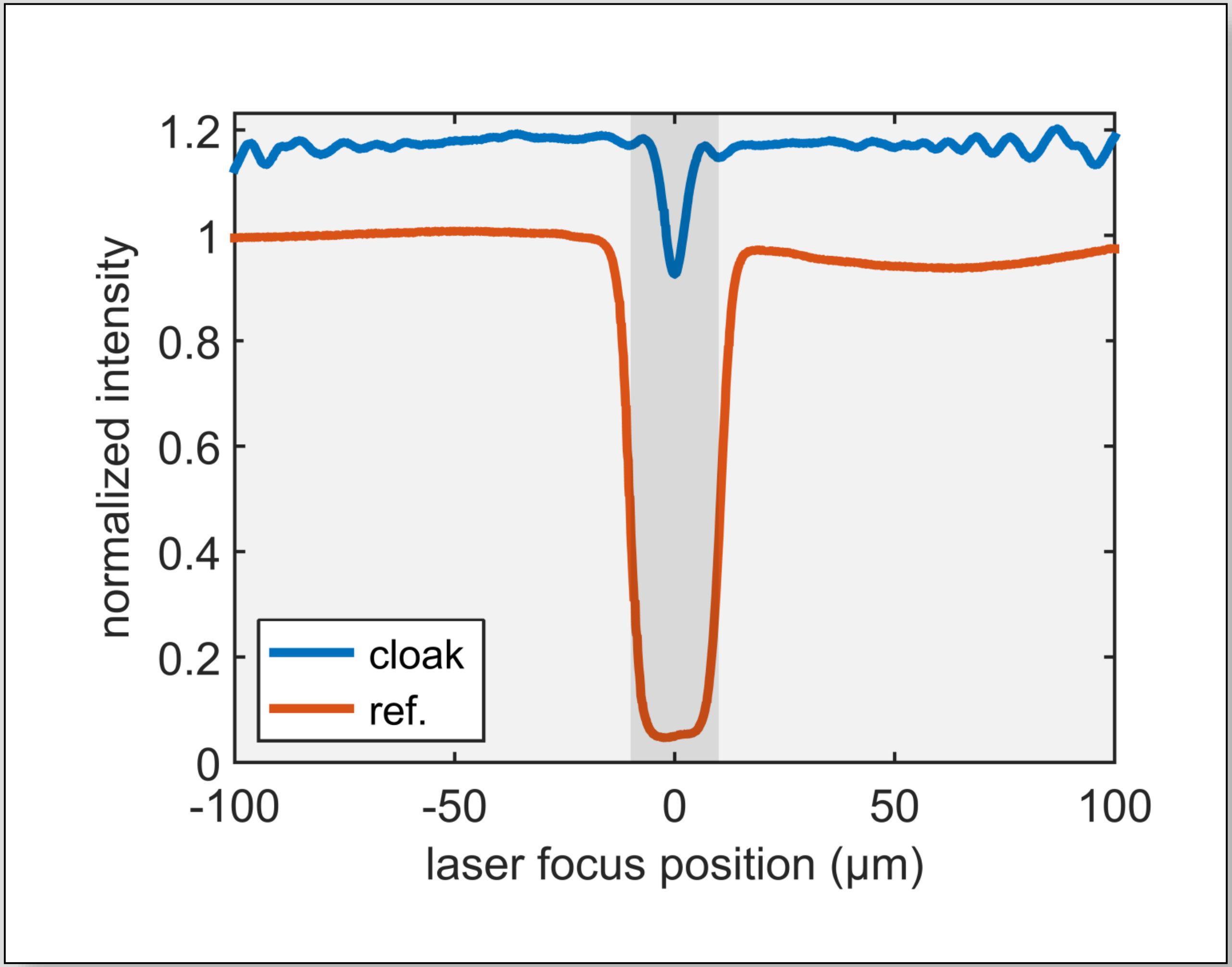


analogous to Pendry's transformation of a point to a circle/sphere; timing is ignored

Electron Micrograph



Optical Characterization

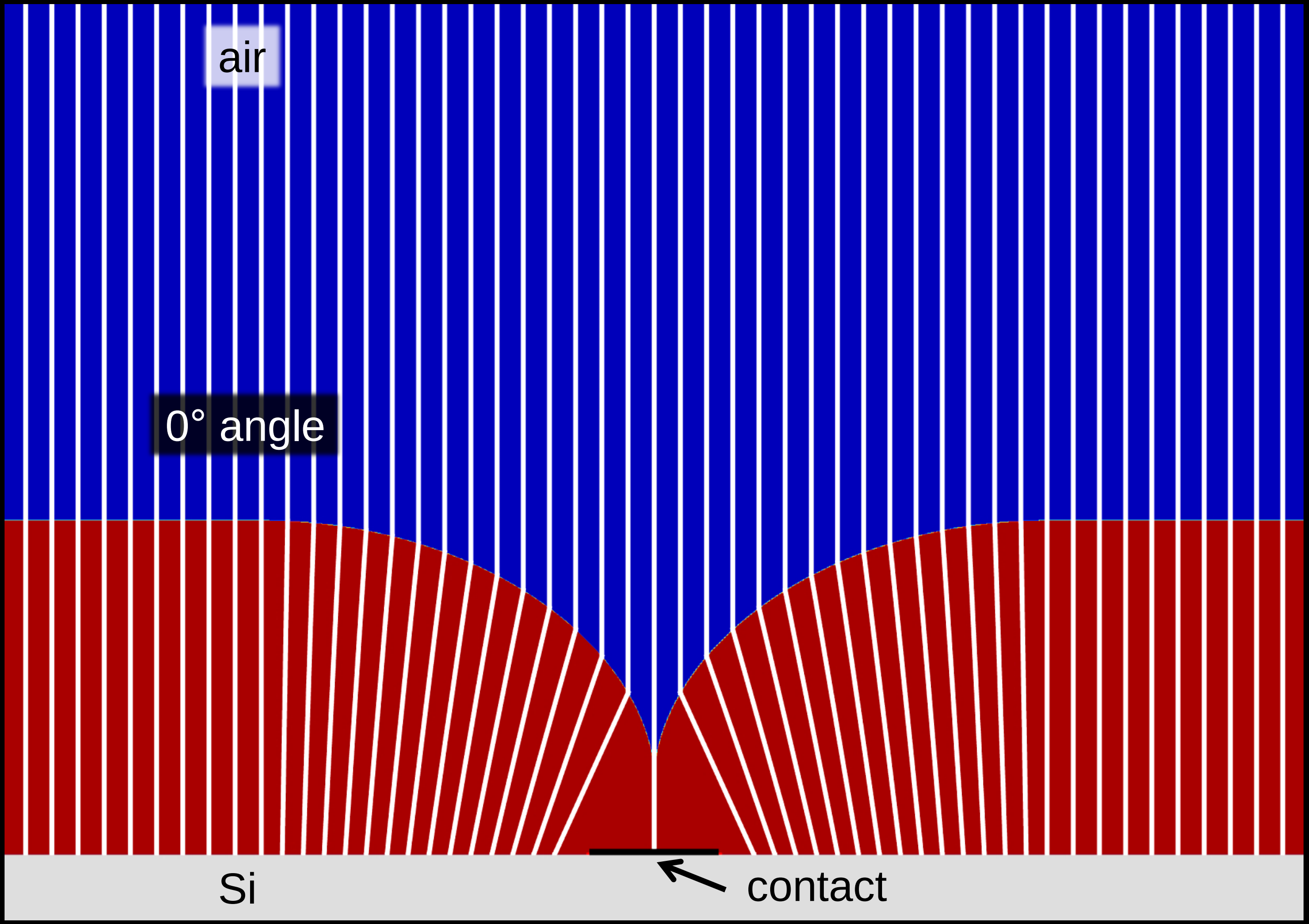


$\lambda = 1.3\,\mu m$ wavelength, normal incidence

Oblique Incidence?

Martin Wegener

Ray Tracing



M.F. Schumann et al., Optica 2, 850 (2015)

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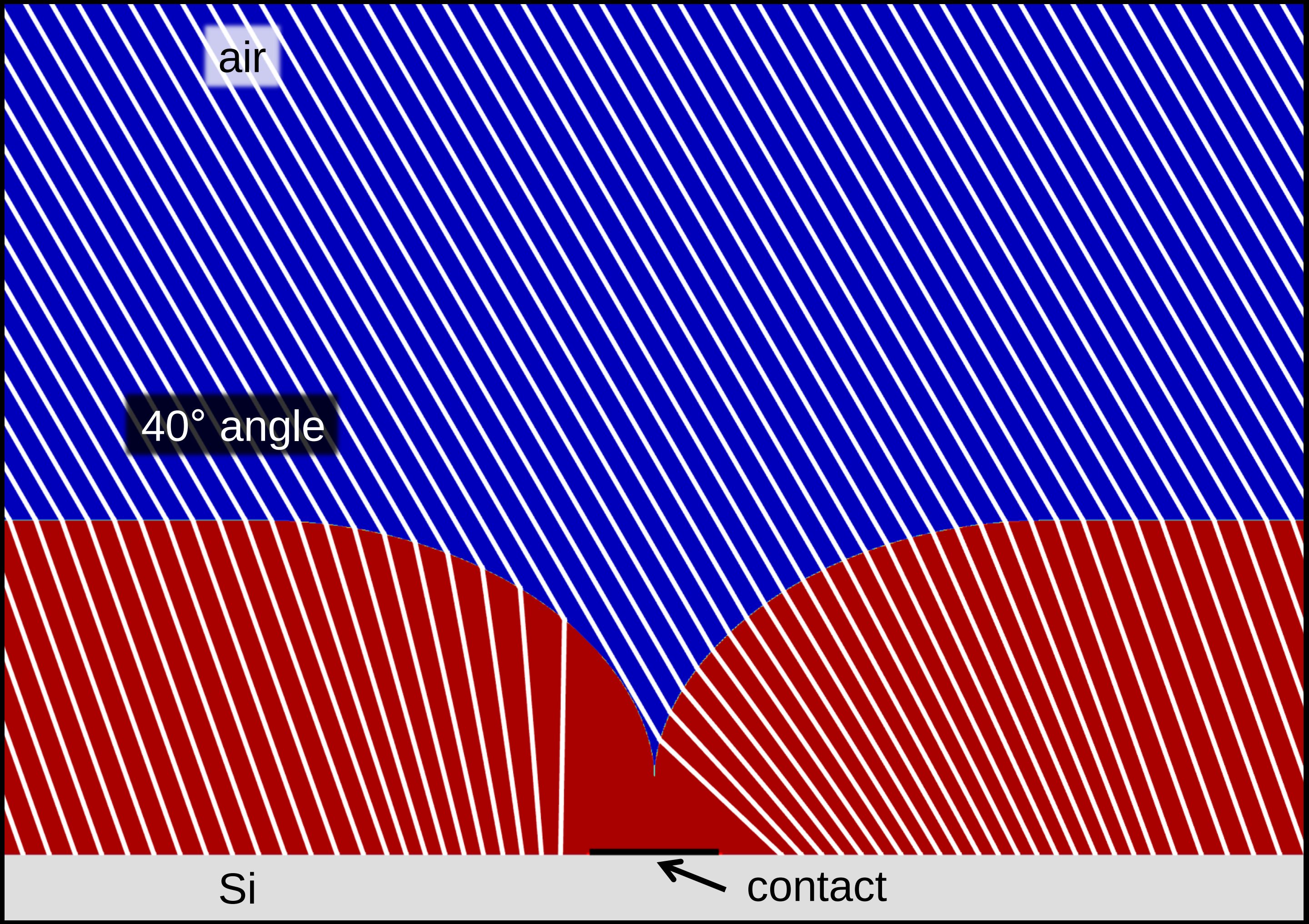
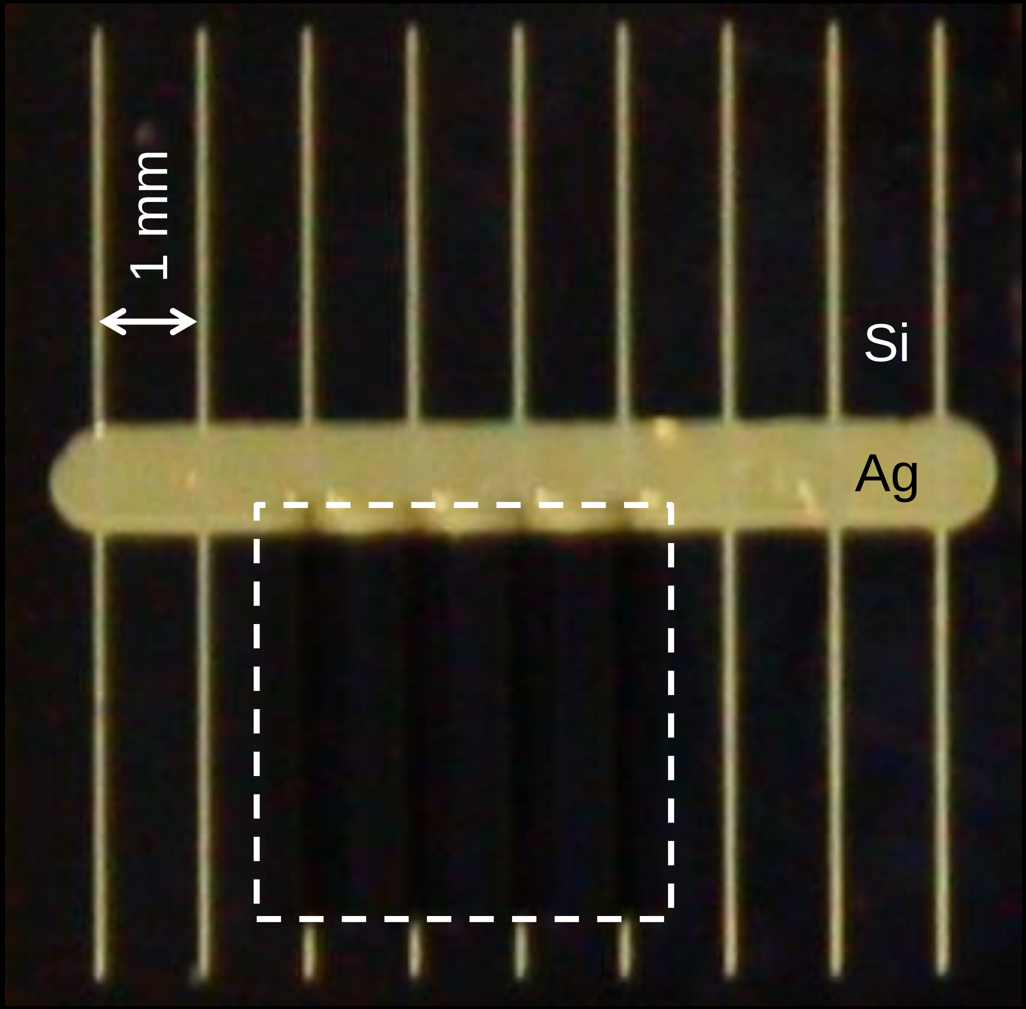


M.F. Schumann et al., Optica 2, 850 (2015)

Contacts are Invisible



imprinted via master on high-end Si solar cell (FZ Jülich), photograph in cleanroom, 2016

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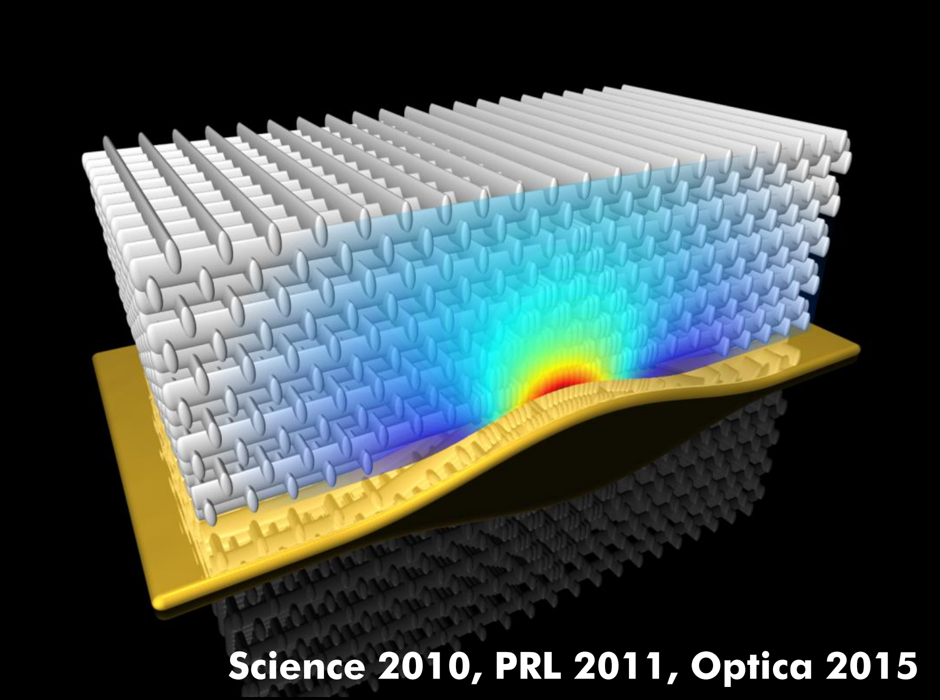
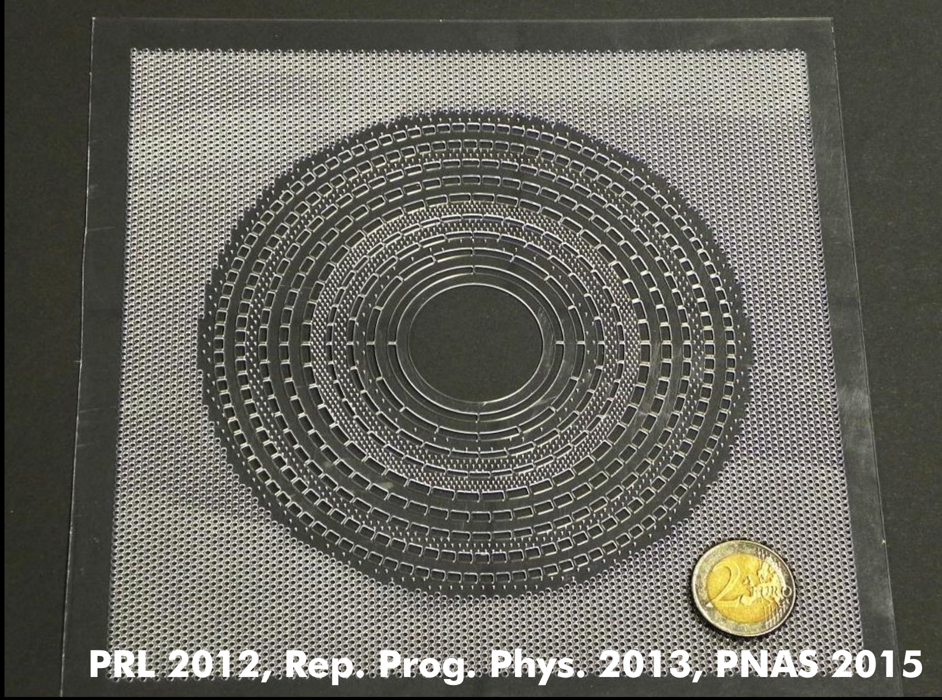
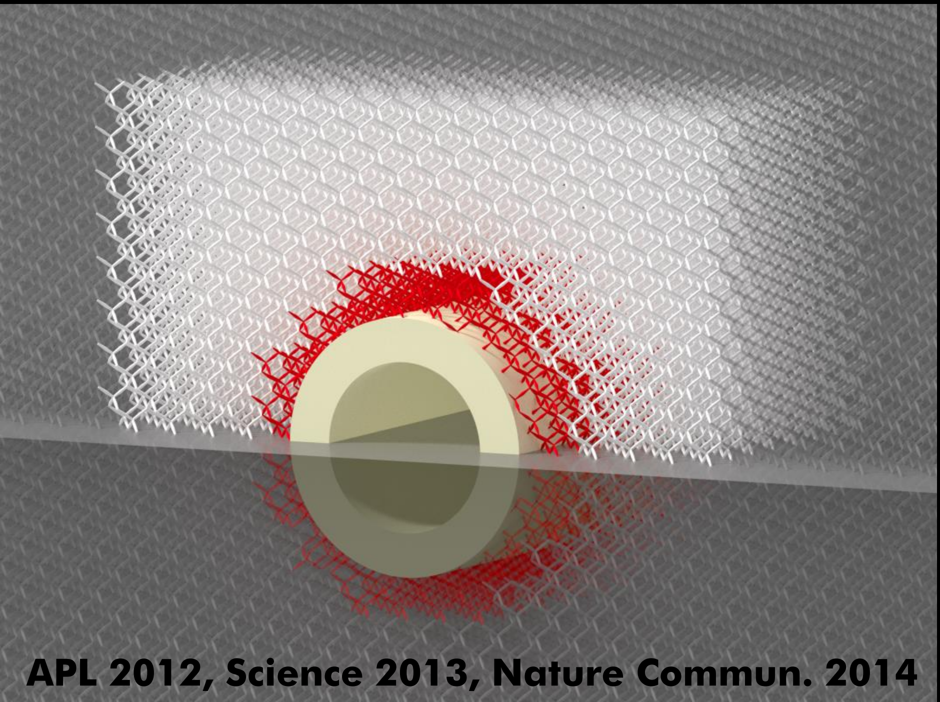
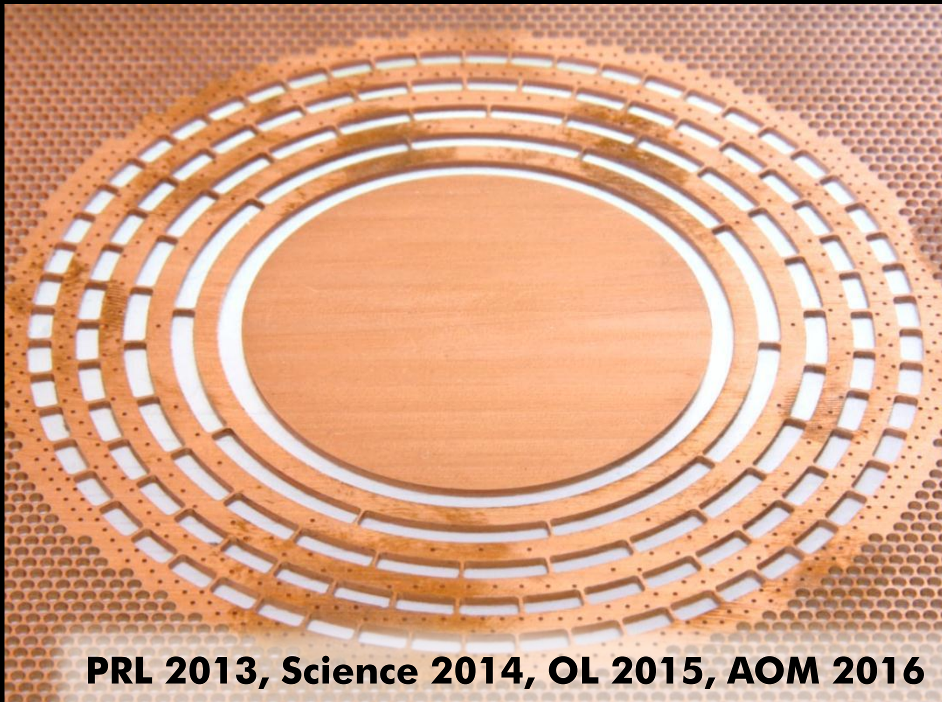

Science 2010, PRL 2011, Optica 2015


PRL 2012, Rep. Prog. Phys. 2013, PNAS 2015


APL 2012, Science 2013, Nature Commun. 2014


PRL 2013, Science 2014, OL 2015, AOM 2016