HAJIM
SCHOOL OF ENGINEERING & APPLIED SCIENCES
UNIVERSITY of ROCHESTER

THE INSTITUTE OF OPTICS

Ph.D. Defense

Practical Invisibility Cloaking

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The Institute of Optics, University of Rochester, NY, U.S.A.

(April 5, 2016)

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Outline

1. Historical invisibility cloaking
2. Scientific cloaking in 2006- “Transformation Optics”
3. Initial ray optics cloaking- Unidirectional
4. ‘Paraxial’ cloaking-
   Multidirectional ray optics cloaking +
   matching full-field/wave “phase”
5. Digital cloaking

Invisibility in History and Fiction

- Greek “Cap of Invisibility” myths
  - Athena, Hermes and Perseus used it.
- Cloak of Invisibility
  - King Arthur, Jack the Giant Killer, Star Trek, Harry Potter, Lord of the Rings
- Chemicals
  - Invisible Man (H.G. Wells)

Invisibility in Magic Shows

- David Copperfield

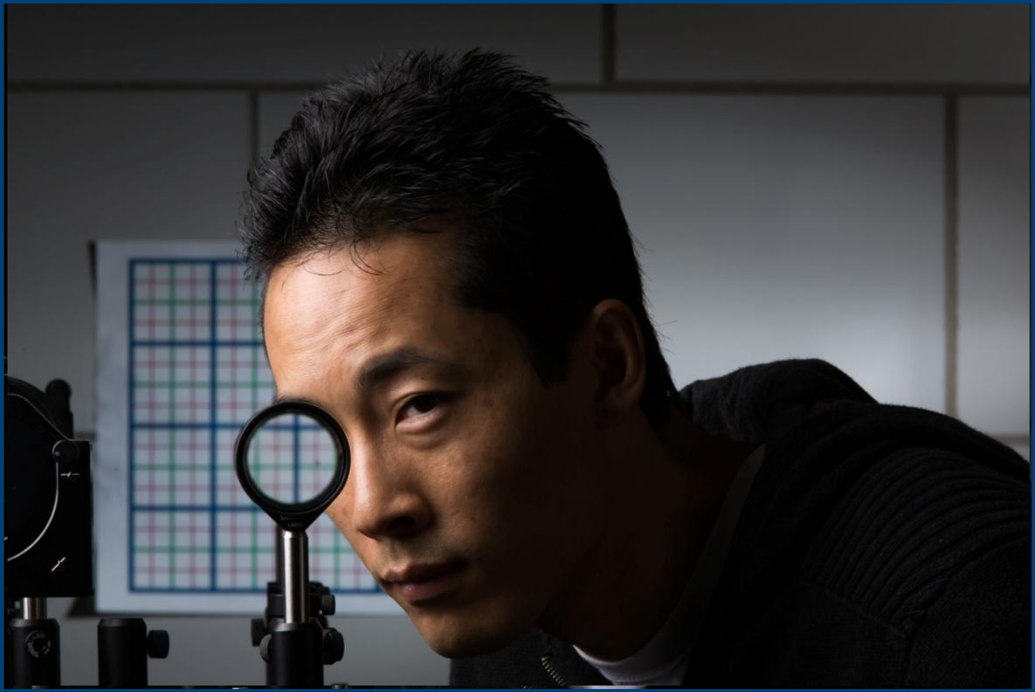
- Science and Technology Museum MadaTech

Define "Cloak" for Talk

- Not a wearable clothing, necessarily

- To "hide"

→ What we'll use



Active Camera Cloaks

- Camera + screen: Schowengerdt (1994)
- Tachi Lab, Keio University, Japan
  - Original in 2003 ([Demo])
- Mercedes-Benz campaign in 2012 ([Mercedes-Benz link])
- Land Rover "Transparent Hood" (2014)

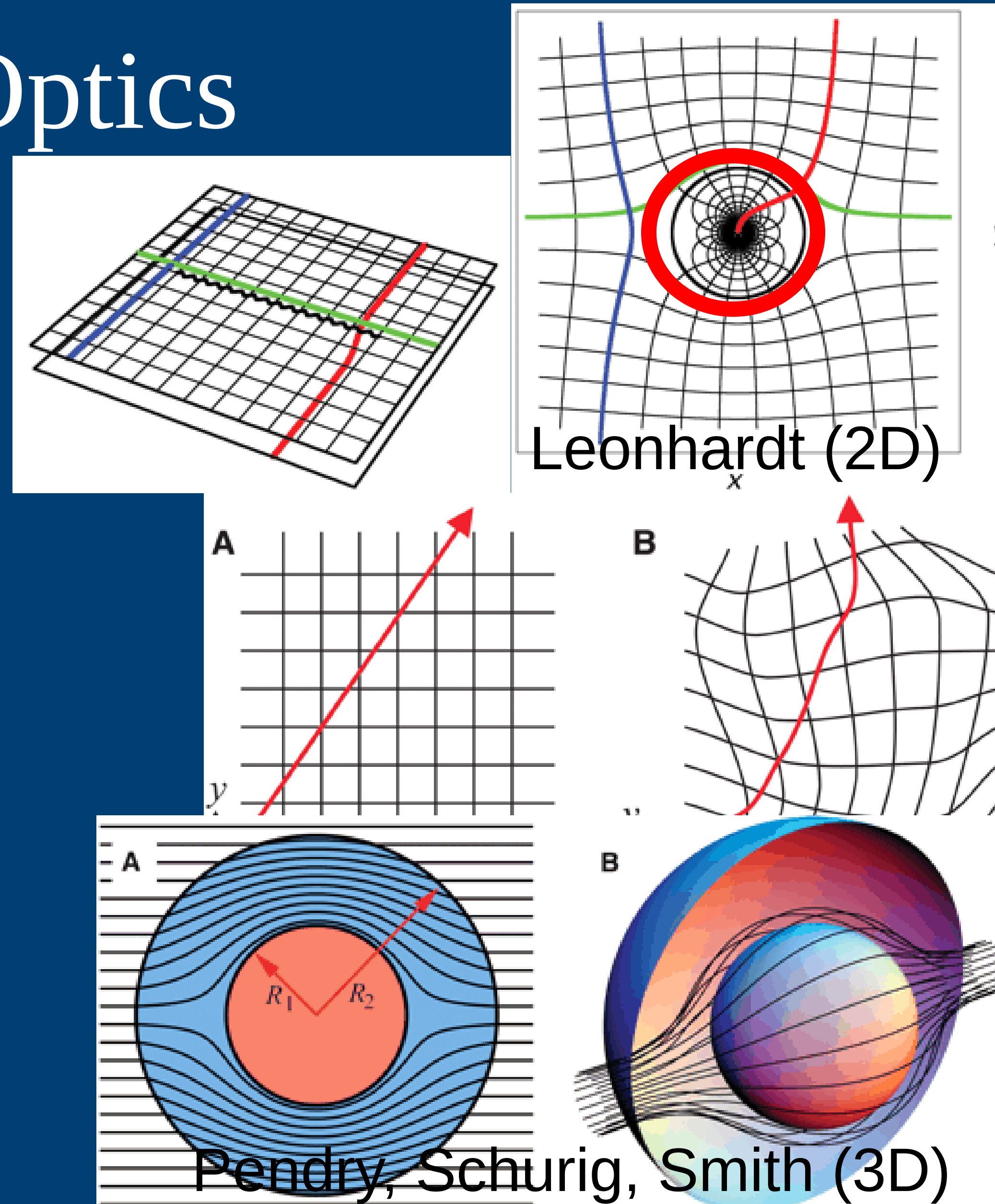
A New Beginning for Scientific Cloaking (2006)

“TRANSFORMATION OPTICS”

Transformation Optics

1. Create virtual space with region that light does not enter.
2. Map this to physical space through coordinate transformation.
3. Build physical space with artificial materials (`metamaterials') only.

→ In 2006, 2 research groups (*Science*)

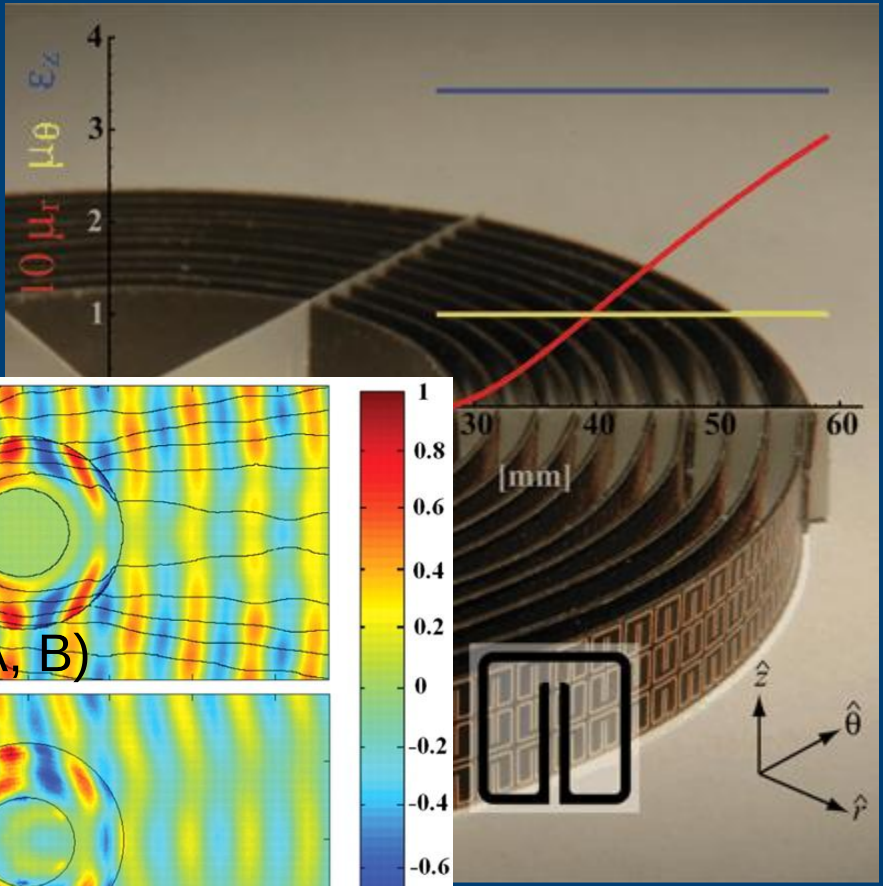


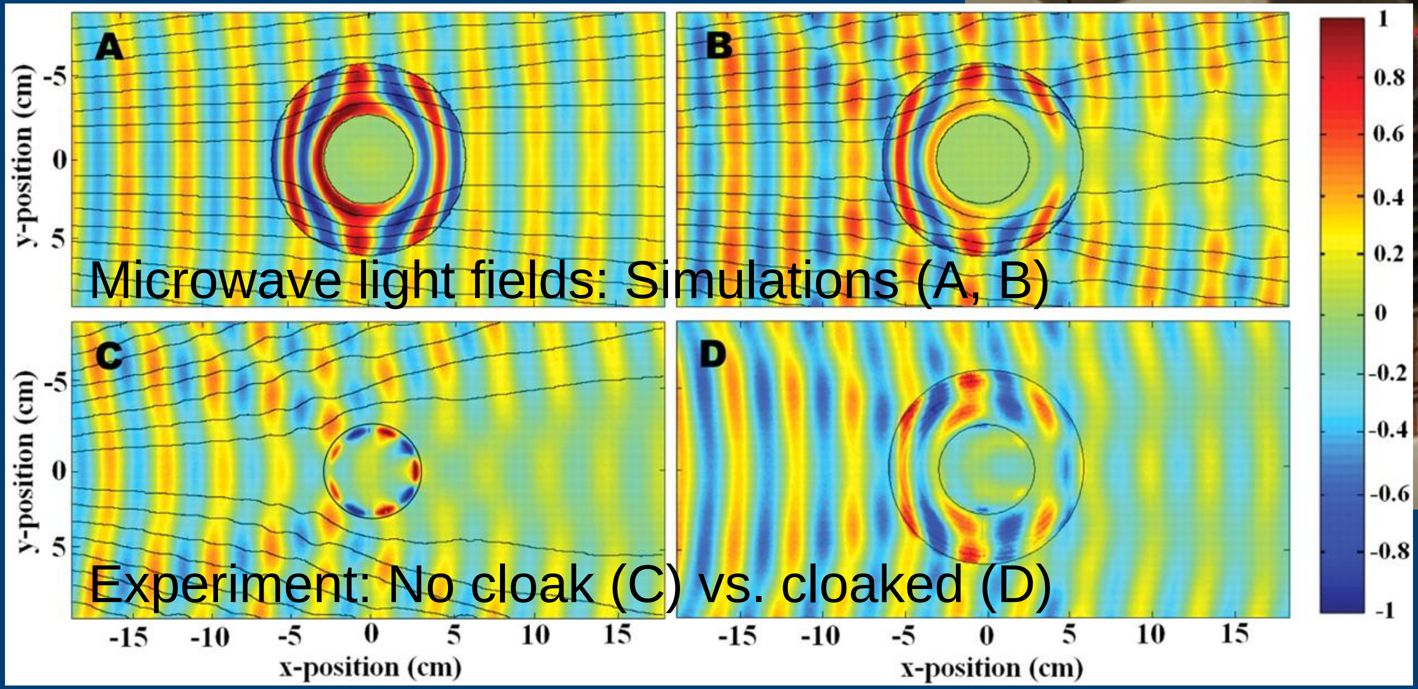
Leonhardt (2D)

Pendry, Schurig, Smith (3D)

Microwave 2D Cloak (2006)

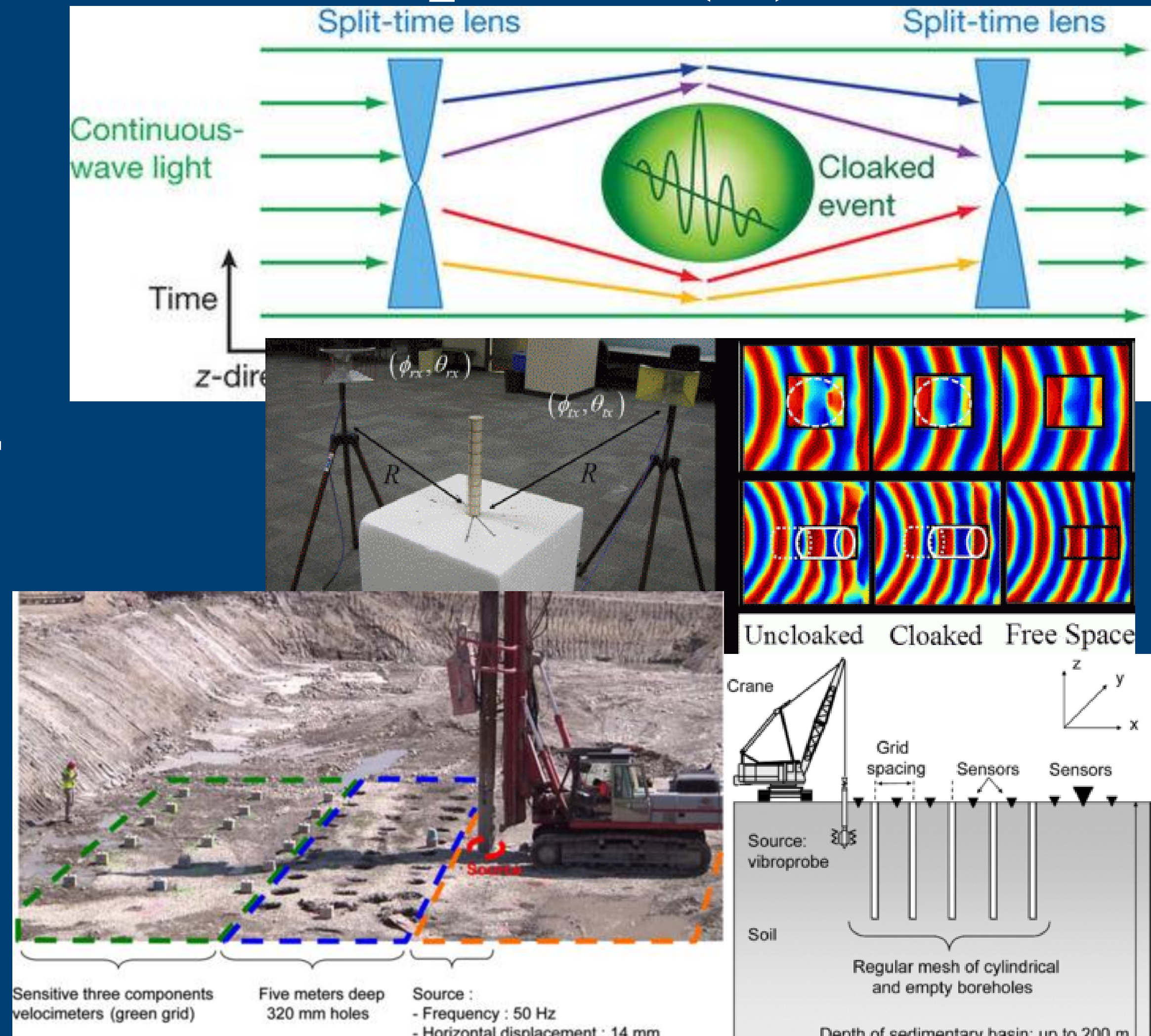
- First demonstration using Transformation Optics (Schurig et al.)
- For 2D, microwave using “split-ring resonators” (metamaterial)



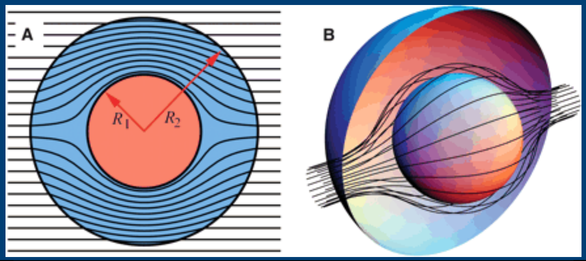


Transformation Optics (1)

- Revolutionary for material design applications and cloaking.
- Omnidirectional
- Full field cloaking for entire light wave (phase + amplitude)
- Examples:
  - Time cloaking
  - Thin, radio wave cancelling cloak
  - Seismic cloaking



Why Ray Optics Cloaking?

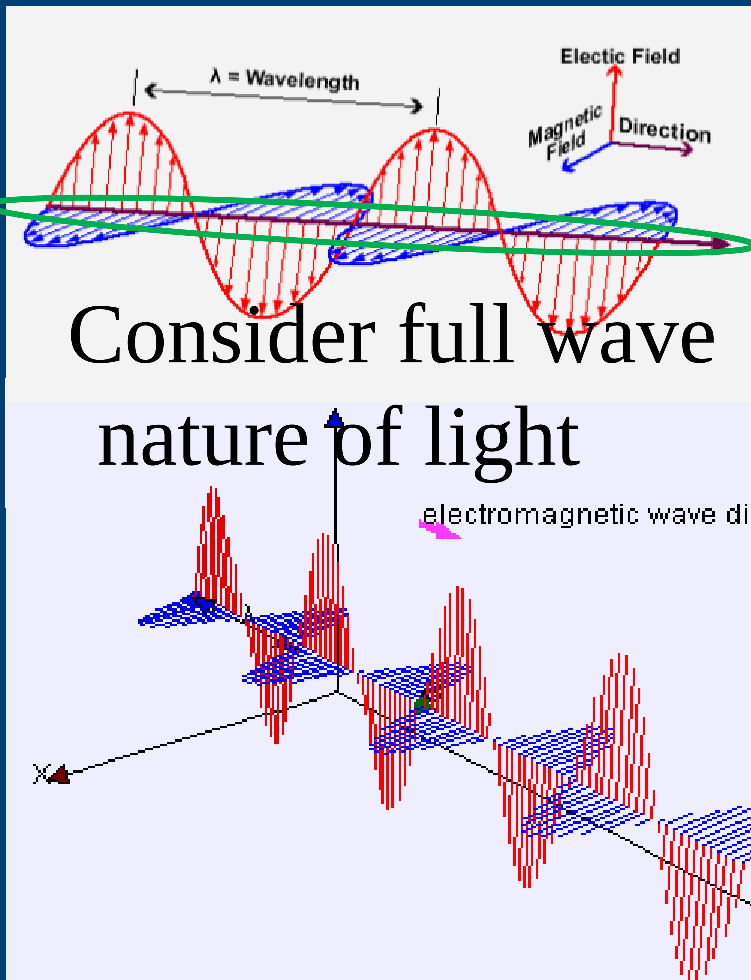


'Ideal' Cloak Properties	Transformation Optics	Initial Ray Optics Cloaking
Broadband	Difficult	Excellent
Visible spectrum		
Isotropic		
Macroscopic scalability		
3D	Some challenges	
Full-field (phase+amplitude)	Excellent	~No (1 or discrete freq.)
Omnidirectional		1 or discrete directions

Unidirectional

RAY OPTICS CLOAKING

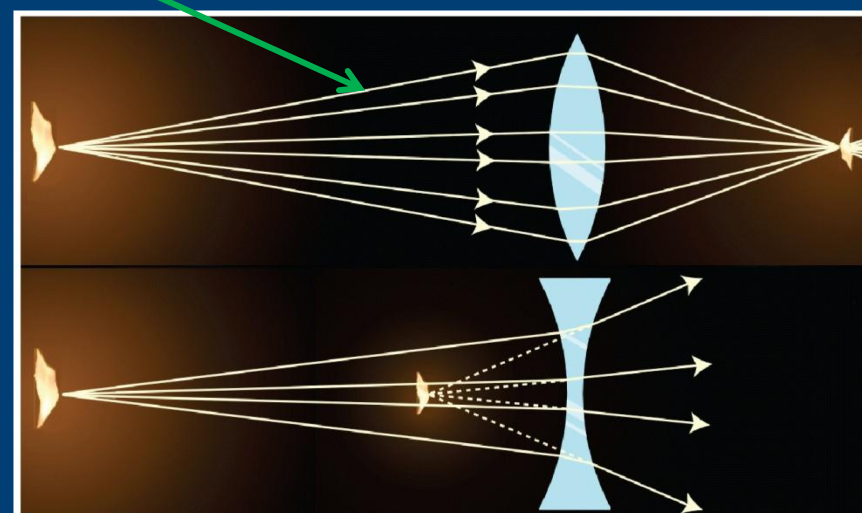
Full Field Optics



Consider full wave nature of light

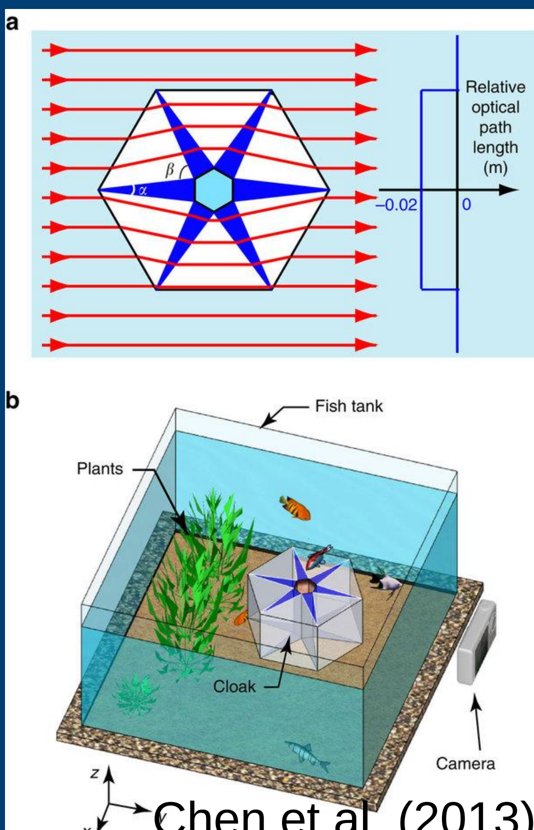
Ray Optics

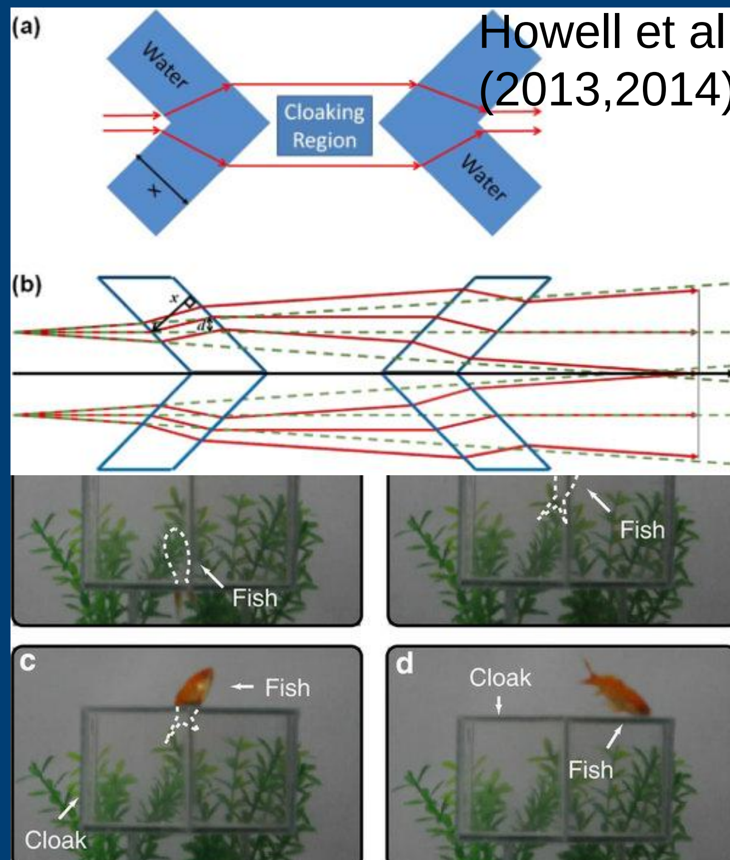
- Only consider direction and power
- Easier

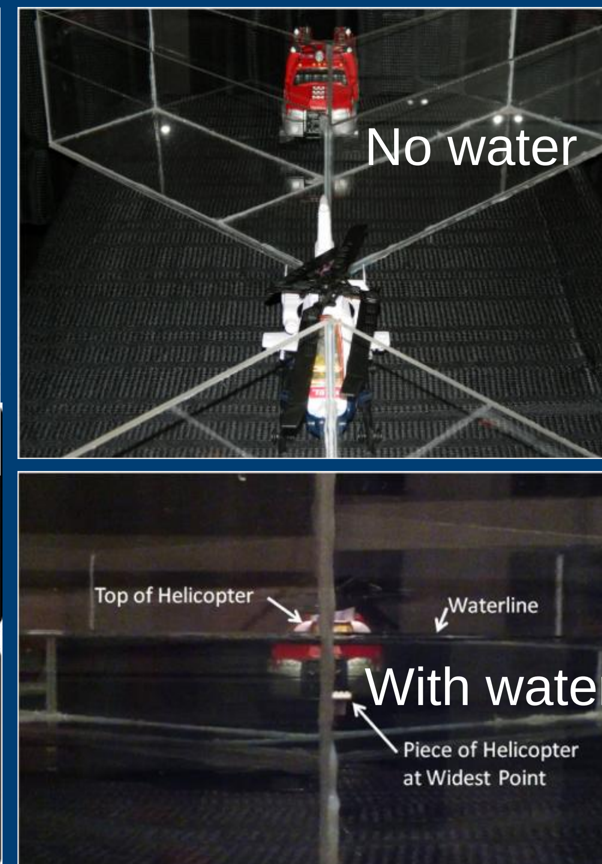


Ray Optics Cloaking

- Macroscopic, visible light cloaks
- Unidirectional, or discretely multidirectional
- Other directions: Background shift, cloak revealed

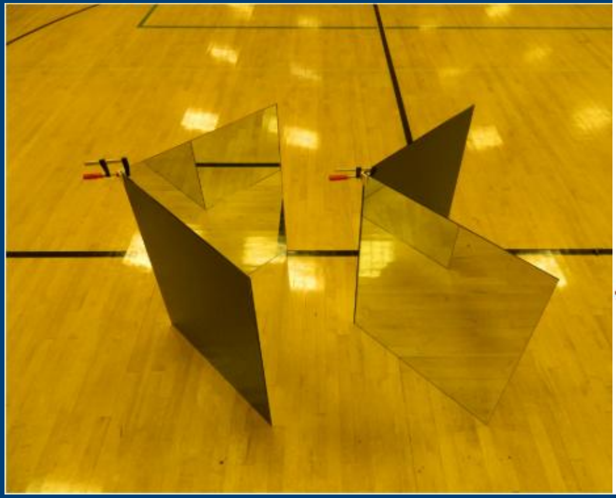


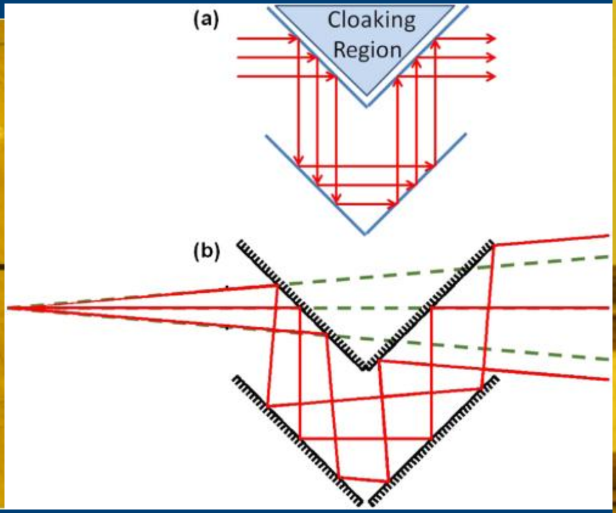




UR Ray Optics Mirror Cloak (2013)

- University of Rochester (UR)- Prof. John Howell and sons (2013 in arXiv)
- Magnification not 1, unidirectional



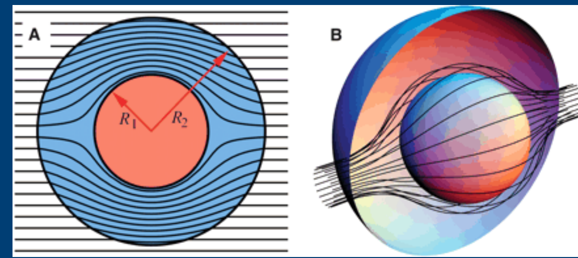


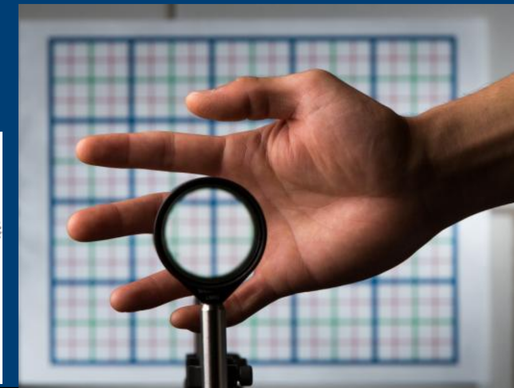
[J. C. Howell, J. B. Howell, and J. S. Choi, Applied Optics 53, 1958 (2014).]

Opt. Express 22, 29465-29478 (2014)

PARAXIAL RAY OPTICS CLOAKING

Why Paraxial Ray Optics Cloaking?



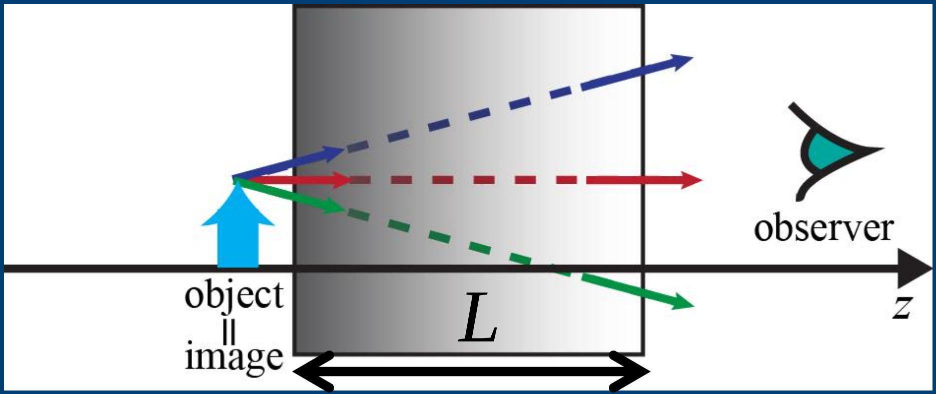


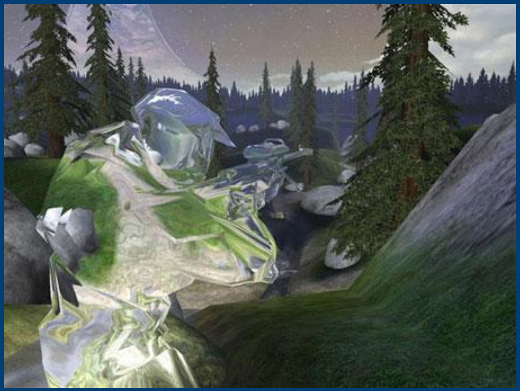
<table>
<tr><th><u>‘Ideal’ Cloak Properties</u></th><th>Transformation Optics</th><th>Paraxial Ray Optics Cloaking</th></tr>
<tr><td>Broadband</td><td rowspan="4">Difficult</td><td rowspan="5">Excellent</td></tr>
<tr><td>Visible spectrum</td></tr>
<tr><td>Isotropic</td></tr>
<tr><td>Macroscopic scalability</td></tr>
<tr><td>3D</td><td>Some challenges</td></tr>
<tr><td>Full-field (phase+amplitude)</td><td rowspan="2">Excellent</td><td>~No (1 or discrete freq.)</td></tr>
<tr><td>Omnidirectional</td><td>Continuous multidirections</td></tr>
</table>

Cloaking: Paraxial Geometric Optics

- Use 'paraxial' formalism (small-angle ~30° or less).
- Assume $n=n'=n_{air}=n_{free\ space}=1$.
- Perfect Cloak:
  1. System = <u>Empty space</u> of same length (L)
  2. Non-zero volume hidden
- ABCD Matrix = ?

  'Translation' Matrix





→ Object + device = **<u>empty space</u>**.

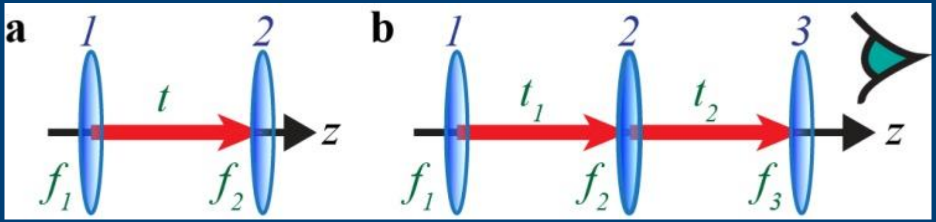
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{PerfectCloak} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$$

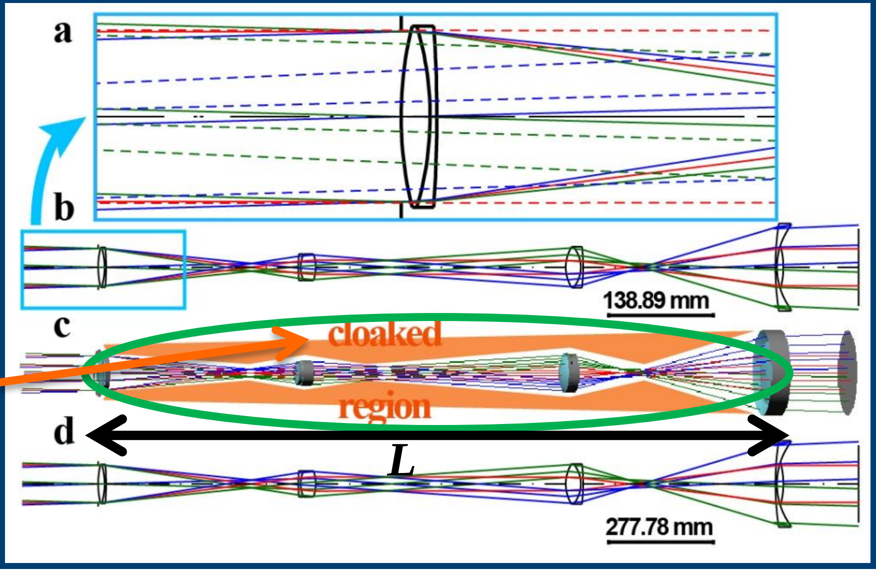
Note: Geometric Optics formalism is inherently 3D and multidirectional.

Paraxial Cloaking Design

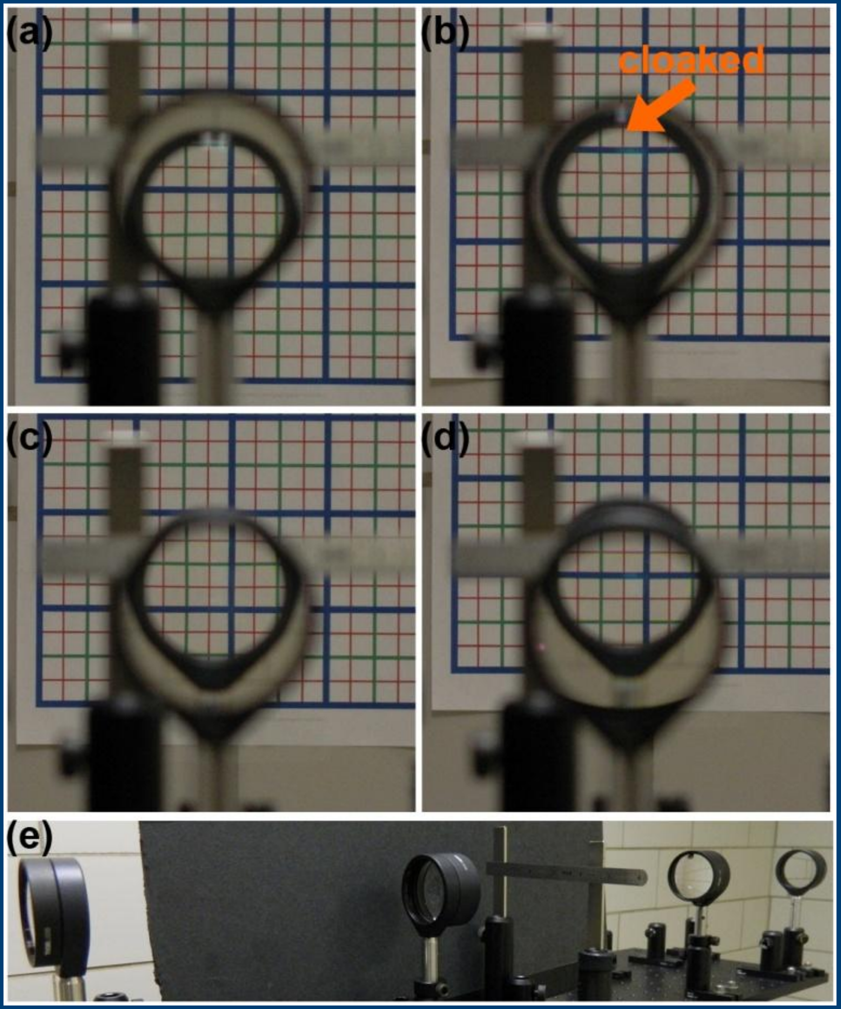
- Try to find **simplest** design that satisfies:
- Use rotationally symmetric, thin lenses.
- 1-2 lenses: No optical power, so no cloakable space.
- 3 lenses: Asymptotically can approach 'perfect' cloak.
- At least 4 lenses required to build 'perfect' cloak:
  1. System = Empty space of same length.
  2. Non-zero volume to hide an object.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{PerfectCloak} = \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}$$





4 Lens "Rochester Cloak" Results



1. Background image matches
   (lenses = empty space).
   → Magnification =1, afocal
   (no net focusing power)
2. Cloaking works for continuous range of directions.
3. Edge effects (paraxial nature), center axis must not be blocked.

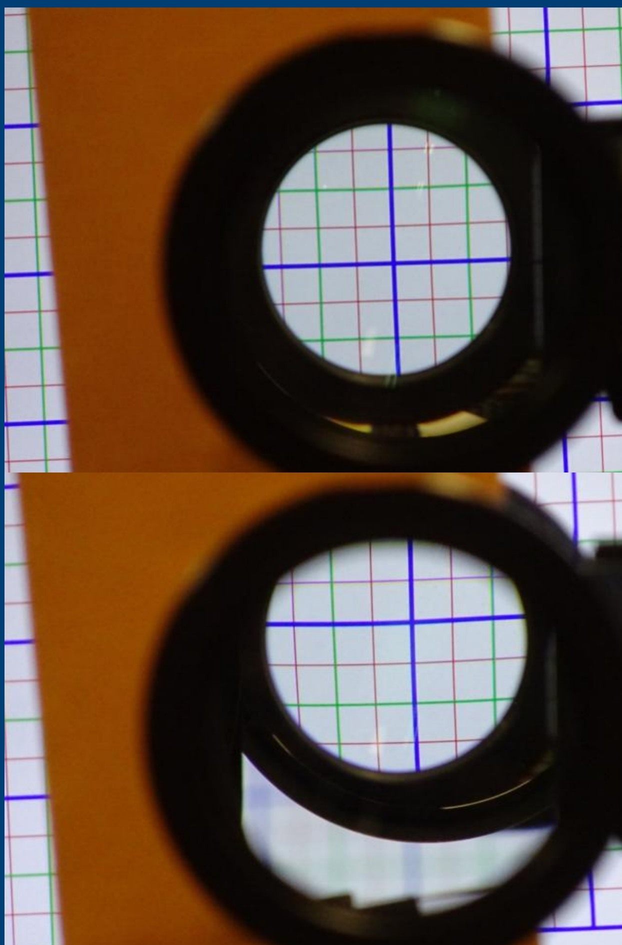
(Optics Express, Vol. 22, pp. 29465-29478, 2014)

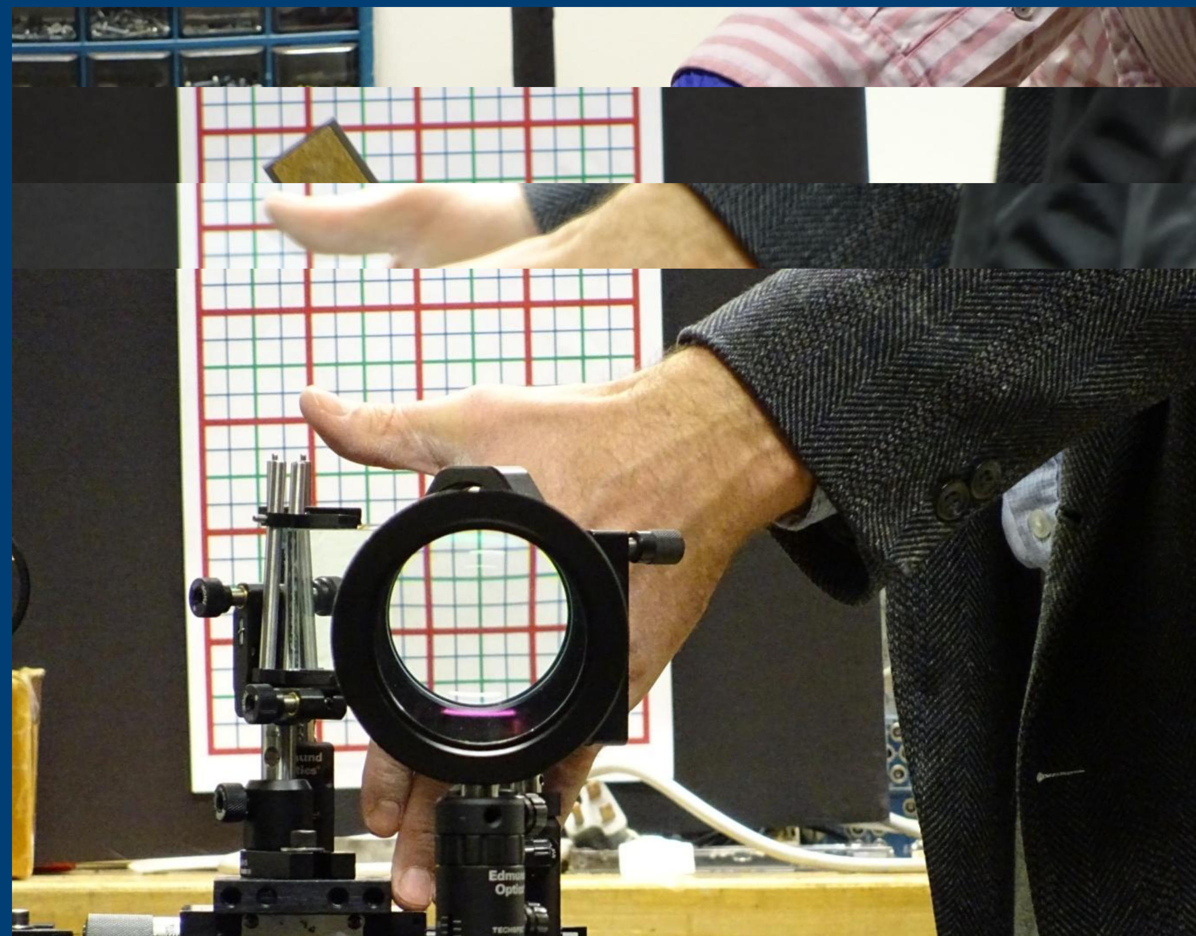
(Photos by J. Adam Fenster / University of Rochester)
(Videos by Matt Mann / University of Rochester)

Rochester Cloak 2

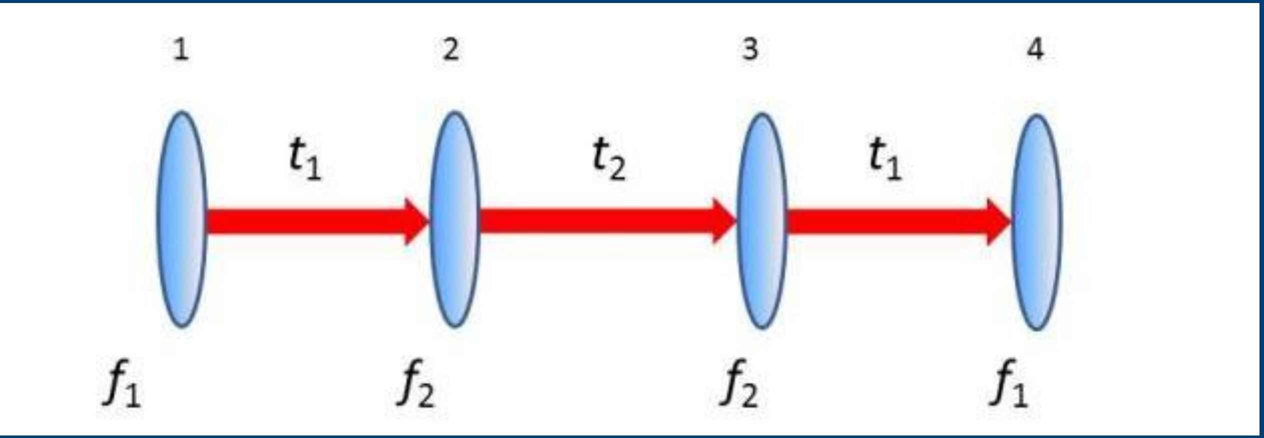
Edmund Optics 3” achromats:

- ~2x field-of-view, 1.5x cloaking diameter (compared to original).
- Center-axis region cloaked as well.





Alignment



- Very sensitive to distances between lenses: ~1% change in t_1, t_2, t_3 can change magnification = 1 to ~50% instead;1mm counts.
- Tips:
  - Account for lens surface location on mount .
  - Use collimated input beam and check for collimation after lenses 1 & 2, lenses 3 & 4 pairs.
  - Magnification should be 1.
  - t_2 controls the image for multidirectional viewing angles.

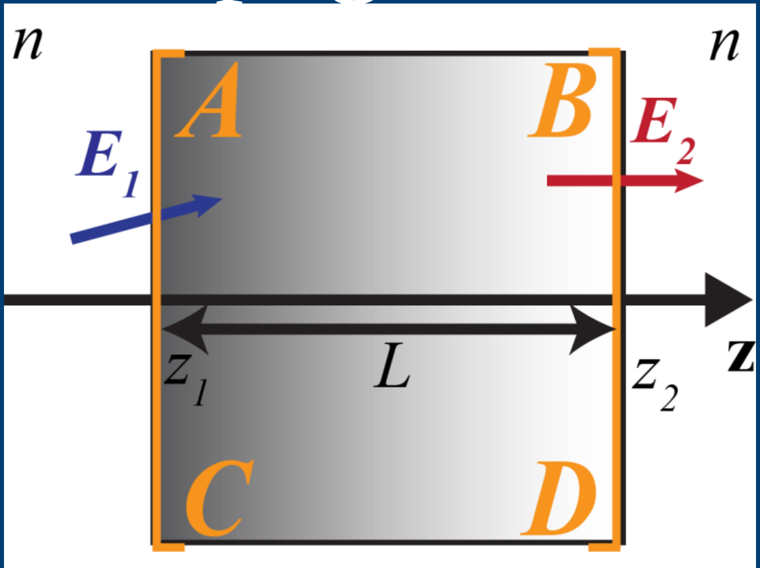
Opt. Express, 23, 15857 (2015)

PARAXIAL FULL-FIELD CLOAKING

Paraxial Full-field Propagation

- Huygens's integral in Fresnel (paraxial) approximation- Diffractive propagation.

(E_2 = output field, E_1 = input field)



$$\tilde{E}_2(x_2,y_2)=\frac{ie^{-ik_0L_0}}{B\lambda_0}\iint_{-\infty}^{\infty}\tilde{E}_1(x_1,y_1)\exp\left\{-i\frac{\pi}{B\lambda_0}\left[A\left(x_1^2+y_1^2\right)-2\left(x_1x_2+y_1y_2\right)+D\left(x_2^2+y_2^2\right)\right]\right\}\mathrm{d}x_1\mathrm{d}y_1,$$

$$L_0=\sum_i n_iL_i=\text{on-axis optical pathlength.}$$

- Fermat's principle- Optical path lengths.

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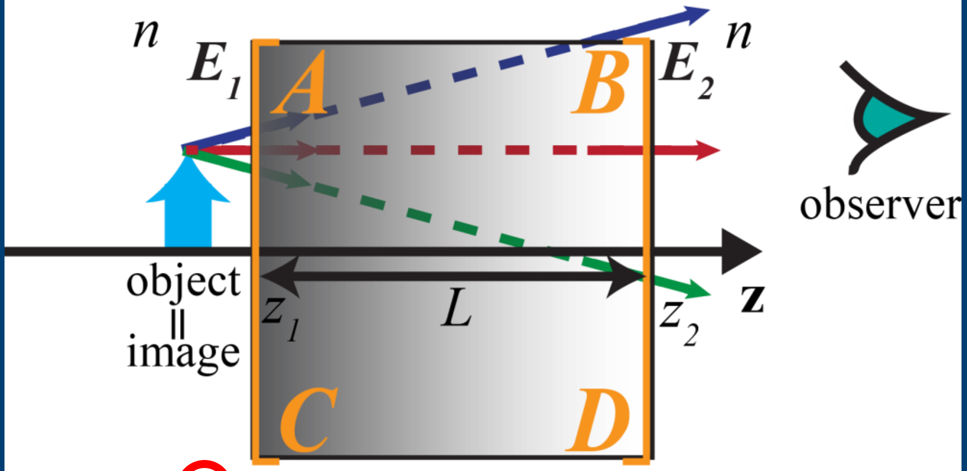
1) A. Siegman, Lasers (1986).
2) S. A. Collins, JOSA 60, 1168 (1970).

Phase-matching



1. Huygens' integral:

$$\tilde{E}_2(x_2, y_2) = \frac{i e^{-ik_0 L_0}}{B\lambda_0} \iint_{-\infty}^{\infty} \tilde{E}_1(x_1, y_1) \exp\left\{ -i\frac{\pi}{B\lambda_0} \left[A(x_1^2 + y_1^2) - 2(x_1 x_2 + y_1 y_2) + D(x_2^2 + y_2^2) \right] \right\} \mathrm{d}x_1 \mathrm{d}y_1,$$

$$L_0 = \sum_i n_i L_i = \text{on-axis optical pathlength.}$$

2. For 'perfect' field cloak:

$$\tilde{E}_2^{\text{perfect cloak}}(x_2, y_2) = \frac{i n e^{-ik_0 nL}}{L\lambda_0} \iint_{-\infty}^{\infty} \mathrm{d}x_1 \mathrm{d}y_1 \tilde{E}_1(x_1, y_1) \times \exp\left\{ -i\frac{n\pi}{L\lambda_0} \left[(x_1^2 + y_1^2) - 2(x_1 x_2 + y_1 y_2) + (x_2^2 + y_2^2) \right] \right\}.$$

3. Absolute phase-matching:

$$e^{-ik_0 L_0} = e^{-ik_0 nL}$$

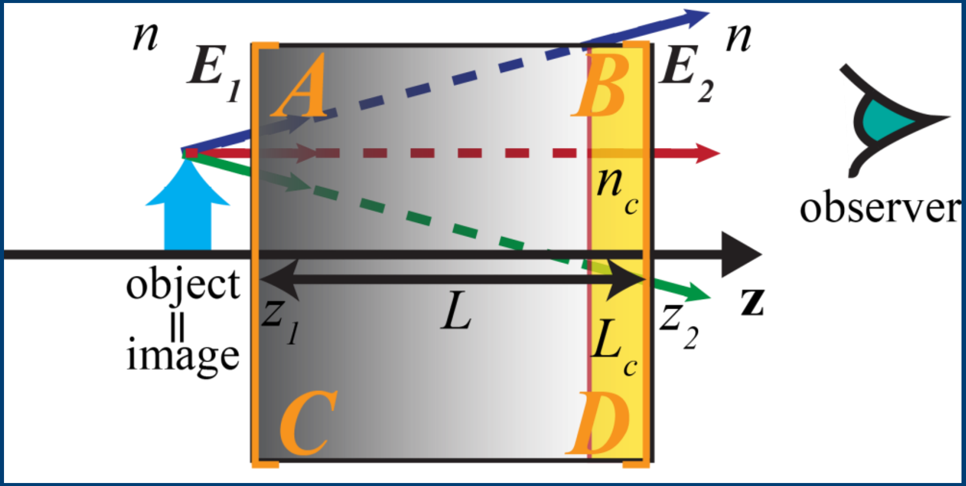
4. Phase-matching to integer multiple of 2π (Broadband):

$$k_0 L_0 \equiv k_0 nL \pmod{2\pi}, \text{ or}$$

$$L_0(\lambda_0) = \sum_i n_i(\lambda_0) L_i \equiv n(\lambda_0) L \pmod{\lambda_0}.$$

A method to match phase

- Start with Ray Cloak.
- Use thin, flat phase-correcting (“c”) plate: No change to ABCD.

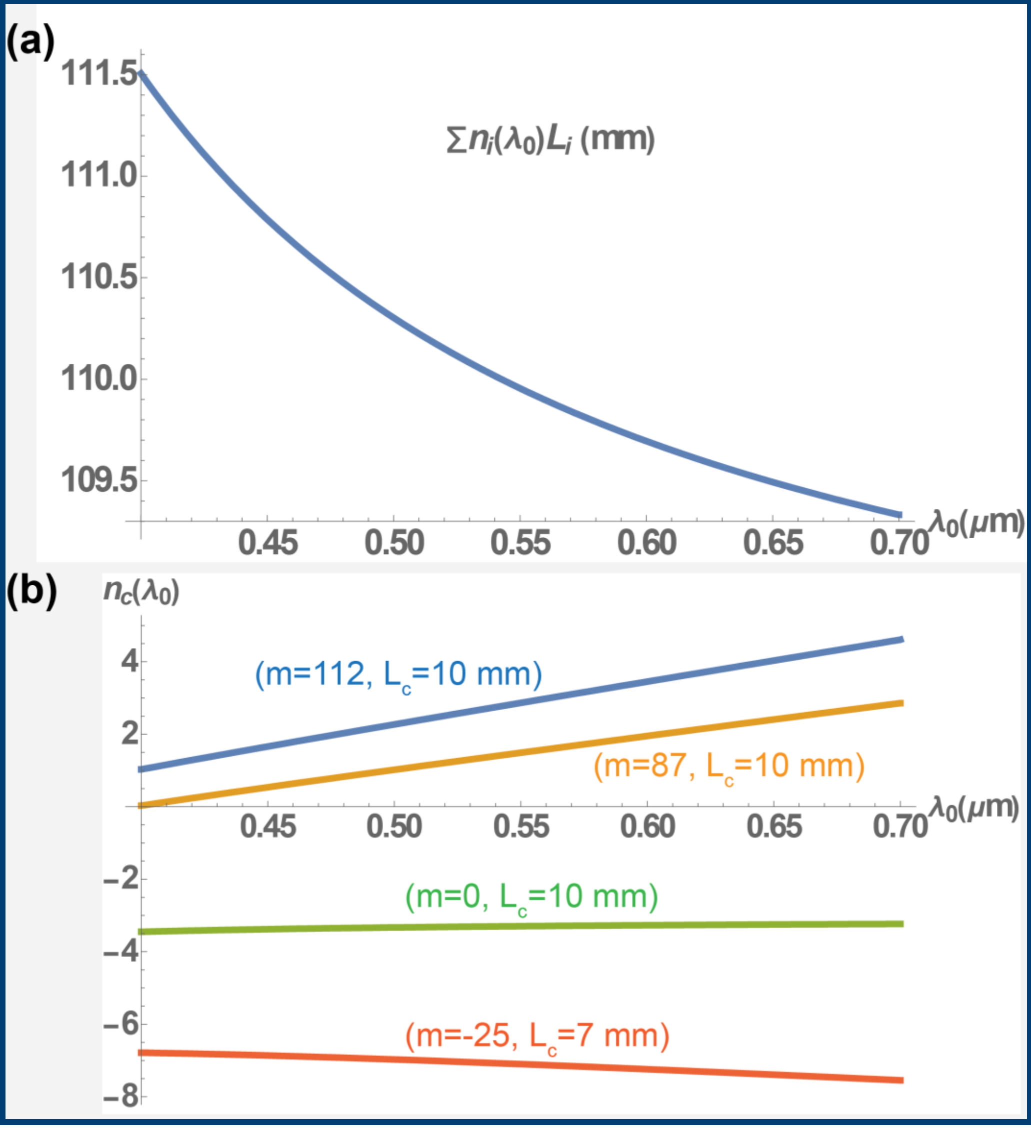


- Index of Correcting Plate (m = integer) :

$$n_c(\lambda_0, m, L_c) = n(\lambda_0) + \frac{1}{L_c}\left\{ m\lambda_0 + \sum_{i=1}^{N} \left[n(\lambda_0) - n_i(\lambda_0) \right] L_i \right\}.$$

Dispersion of Thin Plates

- (a) On-axis optical pathlength for non-air elements of "Rochester Cloak."
- (b) Refractive indices for various phase-correcting plates.
- Values close to current research materials.

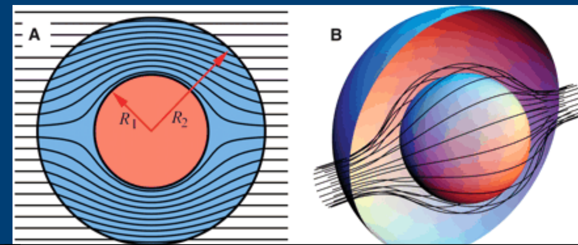


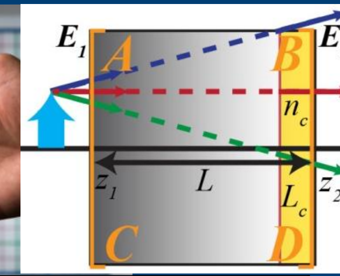
Opt. Express 23, 15857-15862 (2015)

Combine…

PARAXIAL CLOAKING

Cloaking Comparison Redux





'Ideal' Cloak Properties	**Transformation Optics**	**Paraxial Cloaking**
Broadband	Difficult	Excellent
Visible spectrum		
Isotropic		
Macroscopic scalability		
3D	Some challenges	
Full-field (phase+amplitude)	Excellent	Broadband (theory)
Omnidirectional		Continuous multidirection

- Broadband vs. Omnidirectionality: Cannot achieve all?!
- Anisotropy still not required for paraxial cloaking.
- Isotropic, broadband, omnidirectional cloak possible for ray optics?

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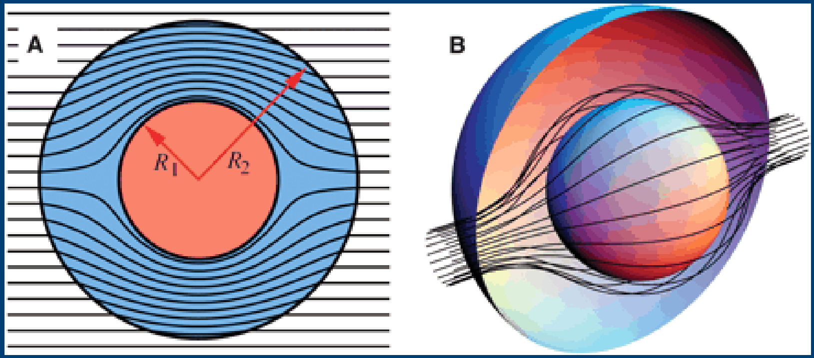
Expand Field-of-View

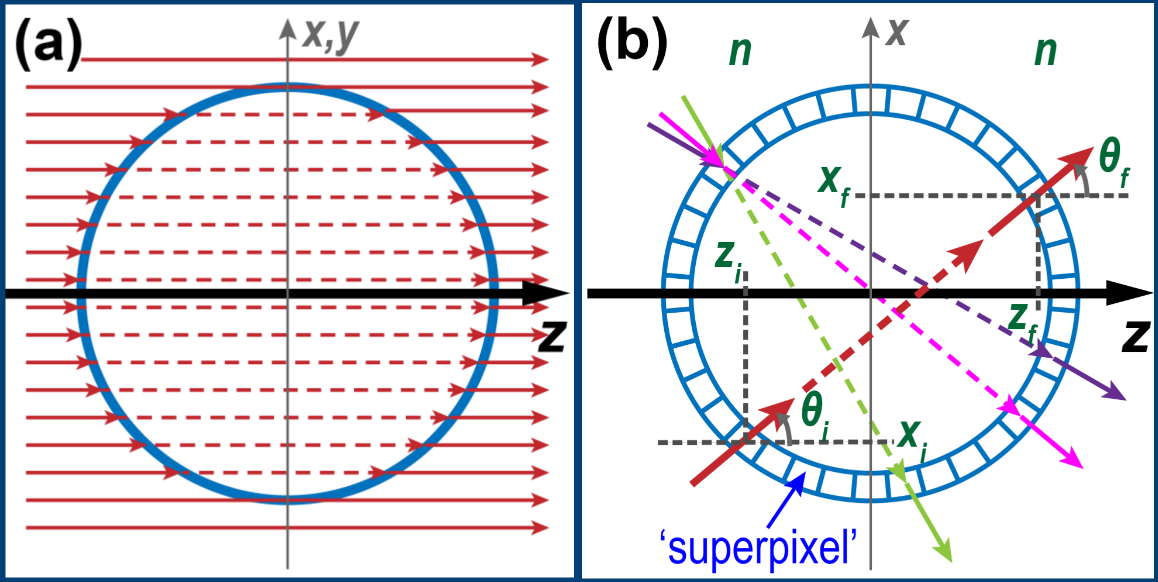
DIGITAL INTEGRAL CLOAKING

Ideal Cloak
"Discretized Cloaking"
(spherically symmetric example)

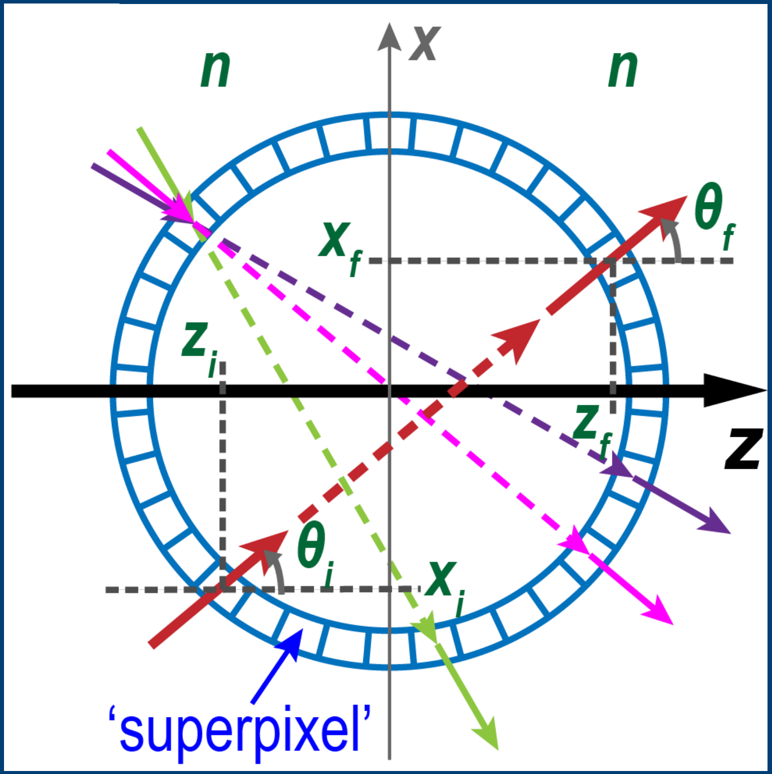
'Ideal' Cloak Properties
Broadband
Visible spectrum
Isotropic
Macroscopic scalability
3D
Full-field (phase+amplitude)
Omnidirectional



Pendry, Schurig, Smith (Science, 2006)



Discretized Cloak



- Can approximate ideal cloak.
- Generalizable to arbitrary shape.
- Pixel-to-pixel mapping:

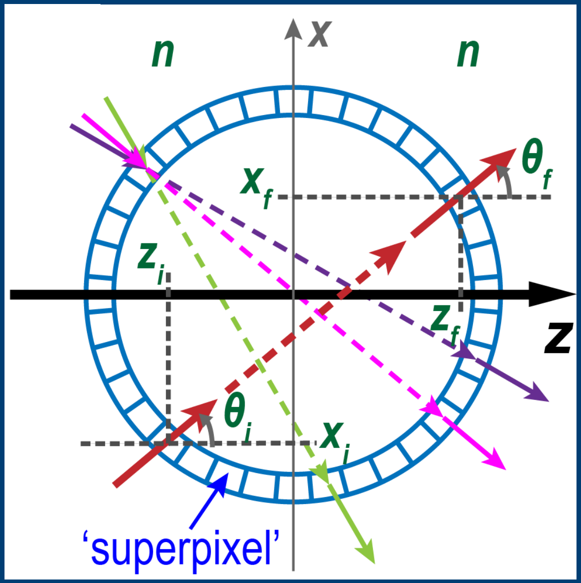
$$\begin{bmatrix} x_f \\ n\tan\theta_f \end{bmatrix}_{z=z_f} = \begin{bmatrix} 1 & (z_f - z_i)/n \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ n\tan\theta_i \end{bmatrix}_{z=z_i}$$

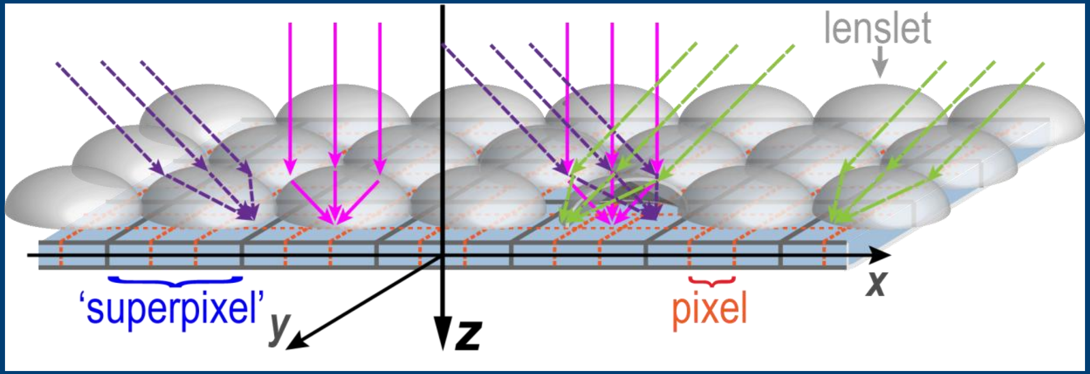
(Choi, Howell, "Digital integral cloaking," *Optica,* (provisionally accepted) (2016))

"Digital Integral" Cloak

Surface now discretized:

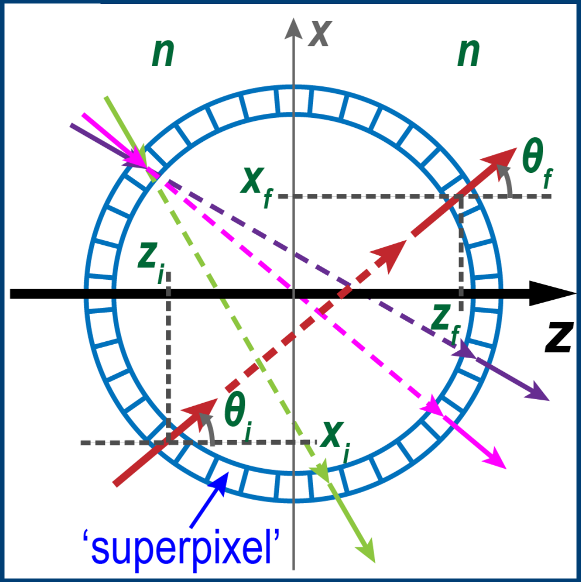
- Digital : Add digital displays, detectors
- Integral: Use 'Integral Imaging'[1]



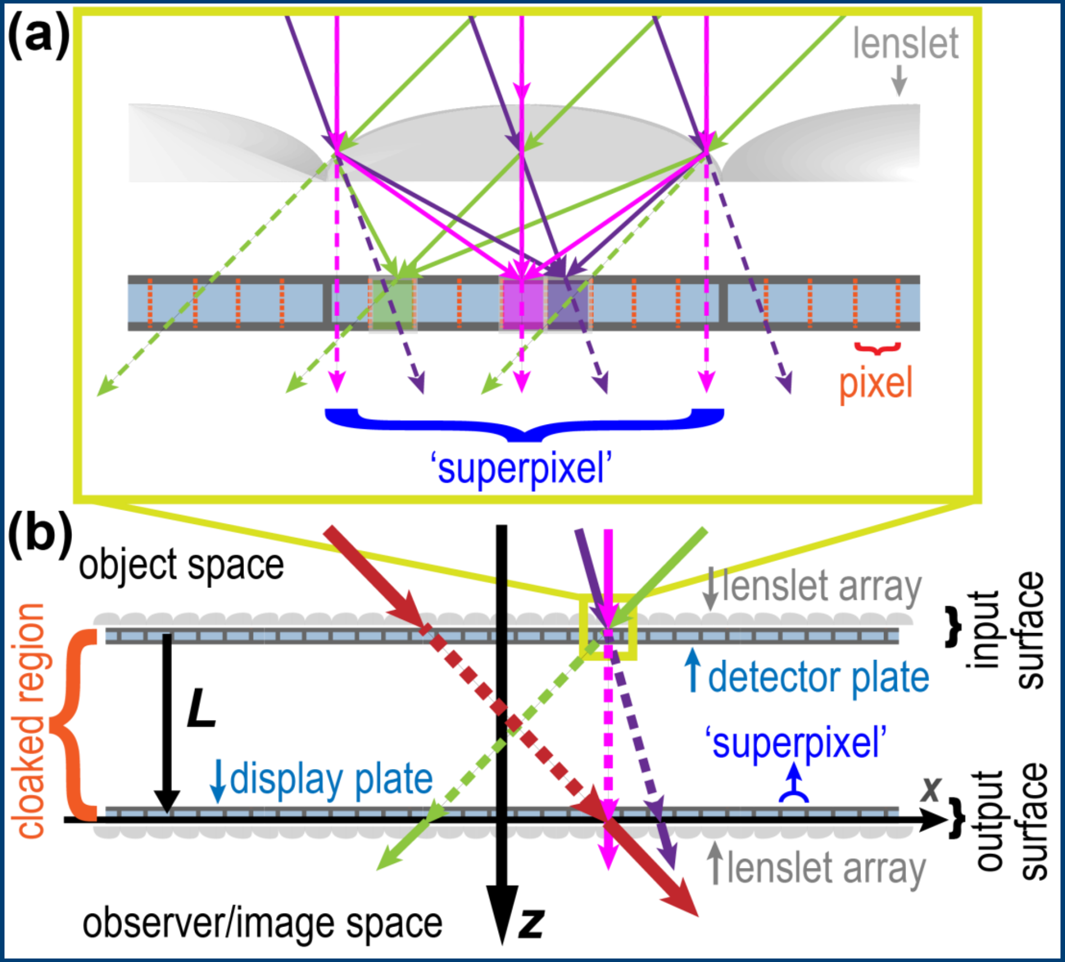


[1] G. Lippmann, C. R. Acad. Sci. 146, 446 (1908).

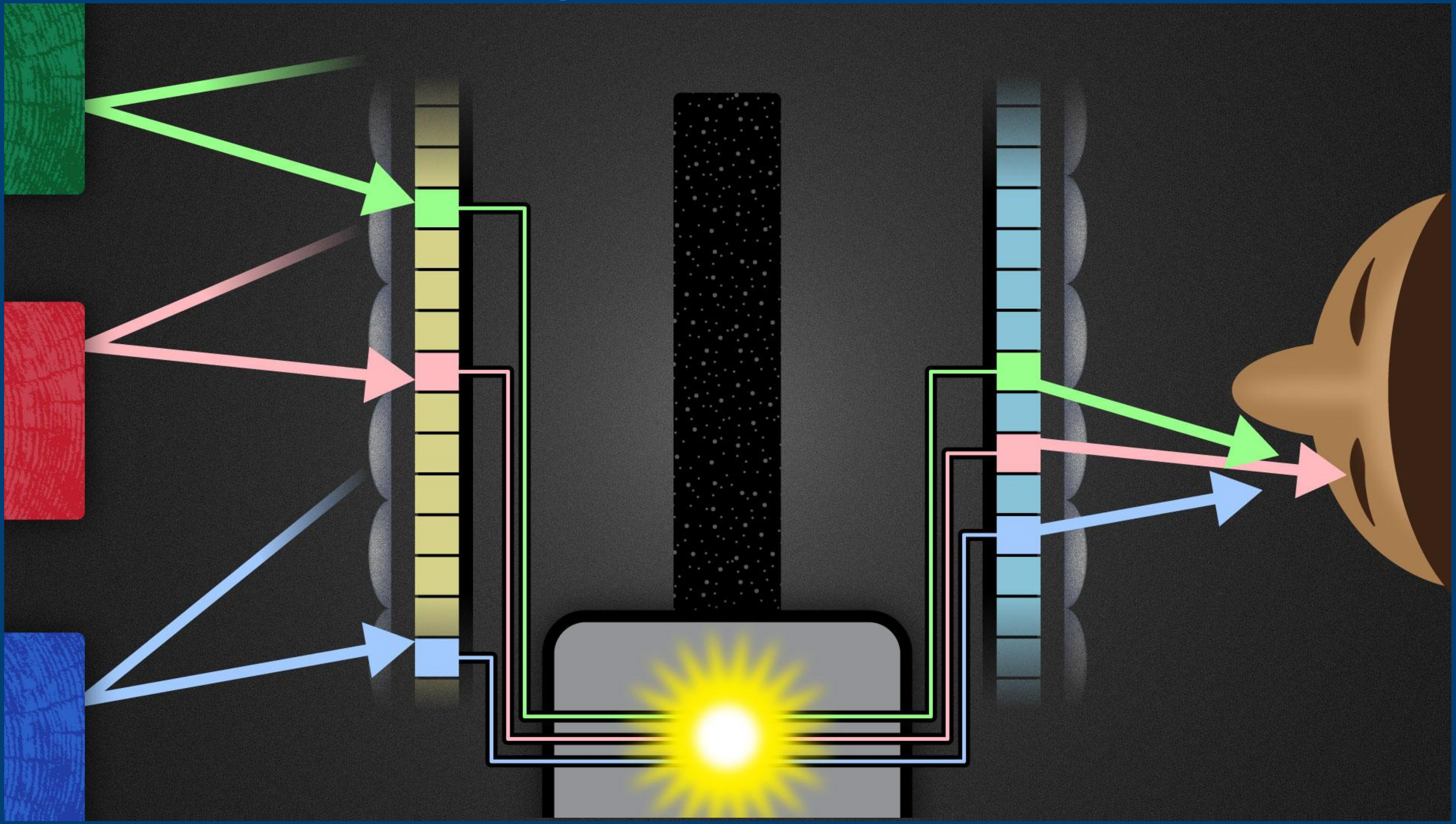
Digital Integral Cloak Example



- Simplify to 2D, planar, ray optics



“Rochester Digital Cloak” Illustration



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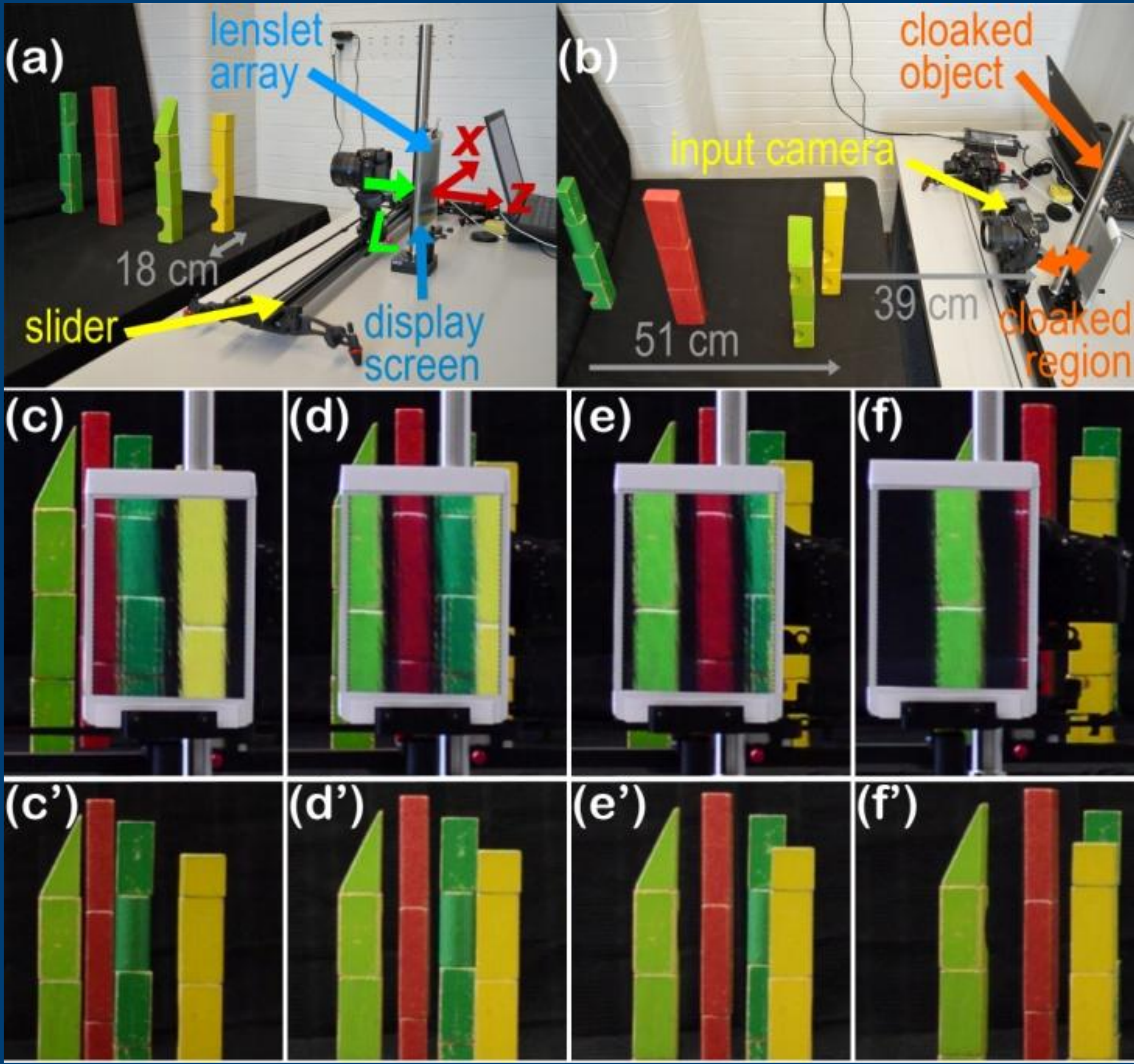
(Mike Osadsciw / University of Rochester)

Setup & Demonstration

- (a)-(b): Setup
- (c)-(f): w/ cloak
- (c')-(f'): w/o cloak
- 60-90 cm depth-of-field
- 29° field-of-view (11° shown)
- 51.5 total "views"
- Output resolution:
  - Angular: 0.56°
  - Spatial: 1.34mm

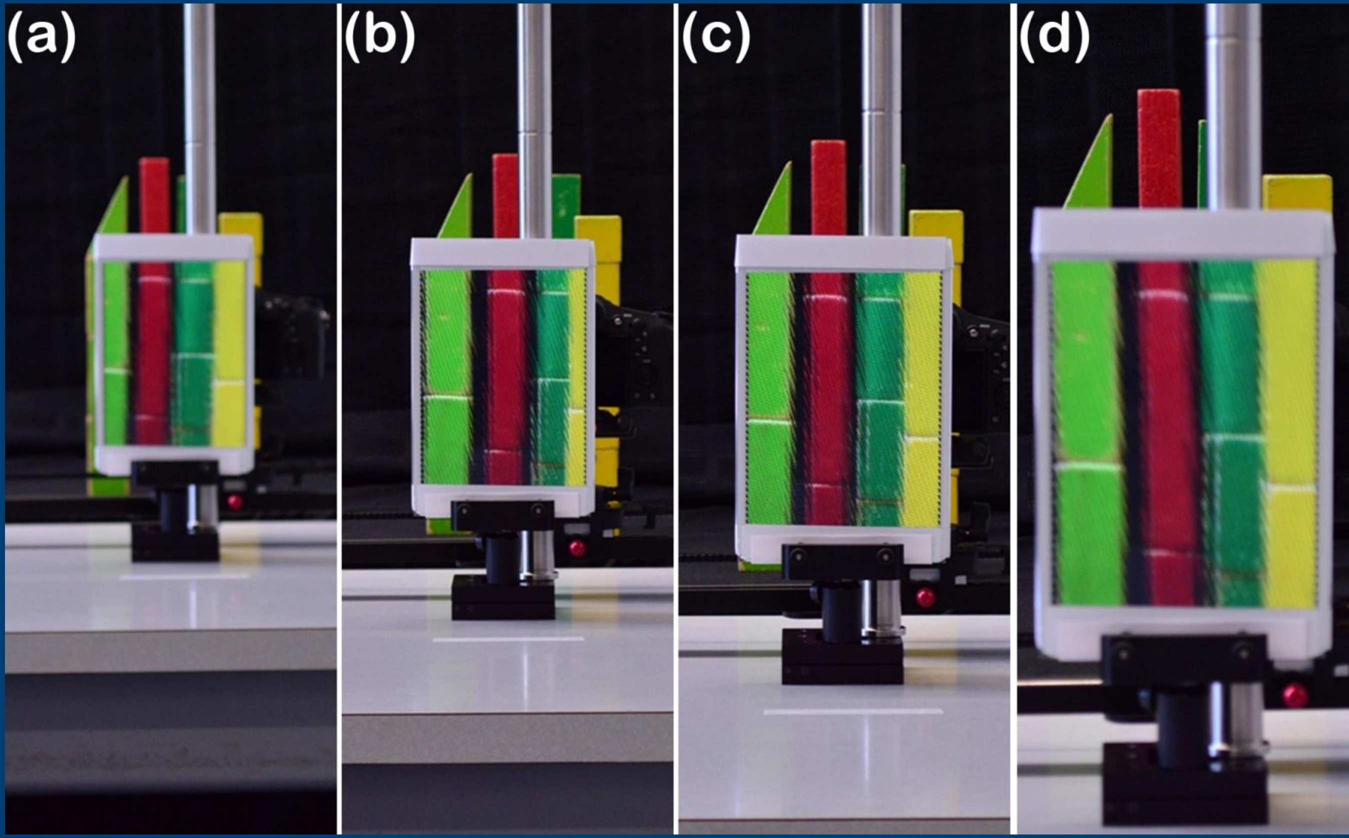


Digital Integral Cloak- Input Scan

Digital Integral Cloak-Horizontal (x) Demo Video

Digital Integral Cloak- Longitudinal (z) Demo

- Distance/FOV from screen:
  a) 272 cm / 2.53°
  b) 235 cm / 2.93°
  c) 203 cm / 3.38°
  d) 150 cm / 4.59°
- Closer → more seen



Digital Integral Cloak- End-to-end Process

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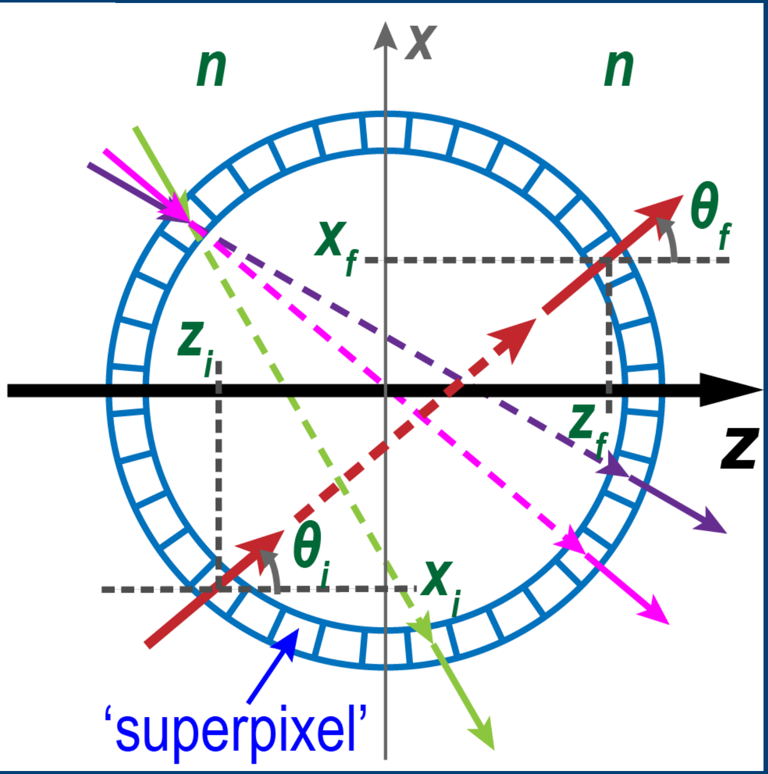
Discretized Cloak



- Simplified to pixel-to-pixel unidirectional propagation.
- Arbitrary and dynamic shape: wearable cloak possible.
- Match phase*:
  - Fixed shape: Fixed material
  - Dynamic shape: Spatial Light Modulator
- Uses commercial technology

$$\begin{bmatrix} x_f \\ n\tan\theta_f \end{bmatrix}_{z=z_f} = \begin{bmatrix} 1 & (z_f - z_i)/n \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ n\tan\theta_i \end{bmatrix}_{z=z_i}$$

*(Optics Express, Vol. 23, Iss. 12, p. 15857 (2015))

Digital Integral Cloak- Improvements

- 3D: Fly’s eye lenslet arrays
- System limited by output, not input: Aberration correction for lenslet arrays
- Real-time
- Optimizations for discretization errors

Acknowledgements

- Professor John Howell
- Aaron Bauer, Kyle Fuerschbach, Robert Gray, Greg Howland, Greg Schmidt, Dr. Andrey Okishev
- University of Rochester Communications- David, Leonor, Adam, Matt, Larry, Mike
- Prof. Allan Greenleaf, James Fienup
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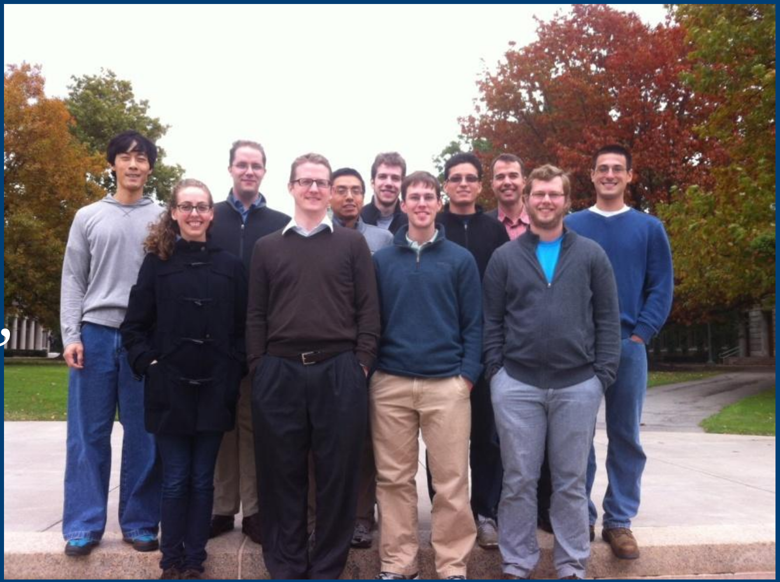
- Edmund Optics



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1) D. Starling, S. Bloch, P. Vudyasetu, J. Choi, B. Little, J. Howell, “Double Lorentzian atomic prism,” *Physical Review A* **86**, 023826 (2012).
2) J. Choi, M. Cho, “Limitations of a superchiral field,” *Physical Review A* **86**, 063834 (2012).
3) H. Rhee, J. Choi, D. Starling, J. Howell, M. Cho, “Amplifications in chiroptical spectroscopy, optical enantioselectivity, and weak value measurement,” *Chemical Science* **4**, 4107 (2013).
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7) J. Choi, J. Howell, “Digital integral cloaking,” *Optica* (provisionally accepted) (2016).

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- Prof. Minhaeng Cho, Dr. Hanju Rhee, Prof. David Allred (BYU), Ryan Cook
- Institute of Optics, Physics:
  - Dir. Zhang, Prof. Fienup, Kari B., Aaron B., Lori, Gina, Maria, Per, Sondra, Connie's, Laura, Lissa
- Howell Group:
  - Curtis Broadbent, Praveen Vudyasetu, Ben Dixon, David Starling, Greg Howland, Steve Bloch, James Schneeloch, Gerardo Viza, Bethany Little, Julian Martinez, Daniel Lum, Chris Mullarkey, Sam Knarr, Justin Winkler, Shurik Zavriyev
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Questions?

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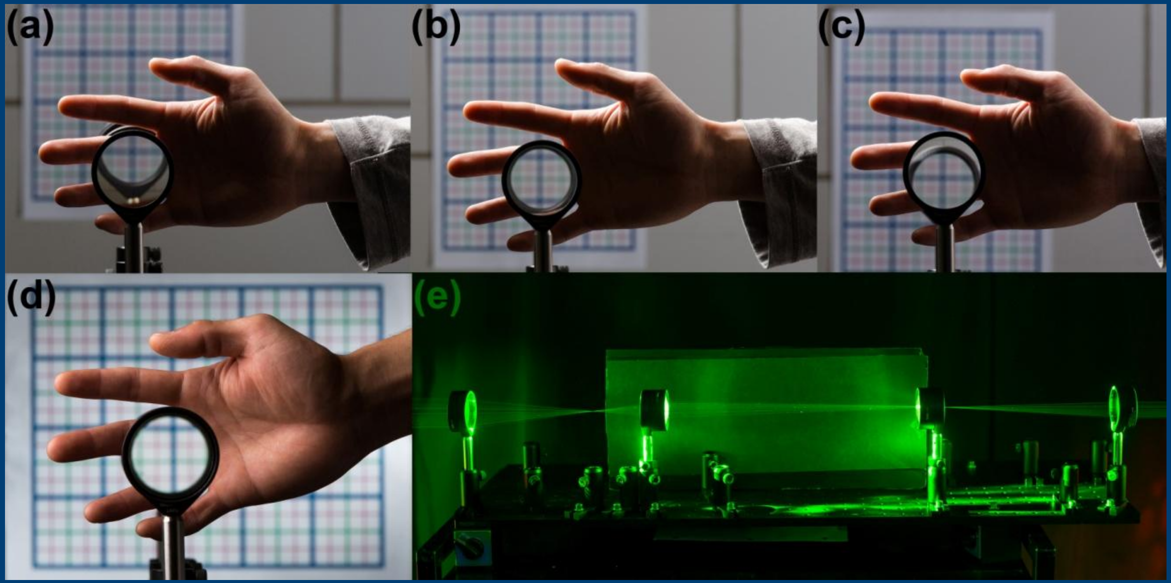
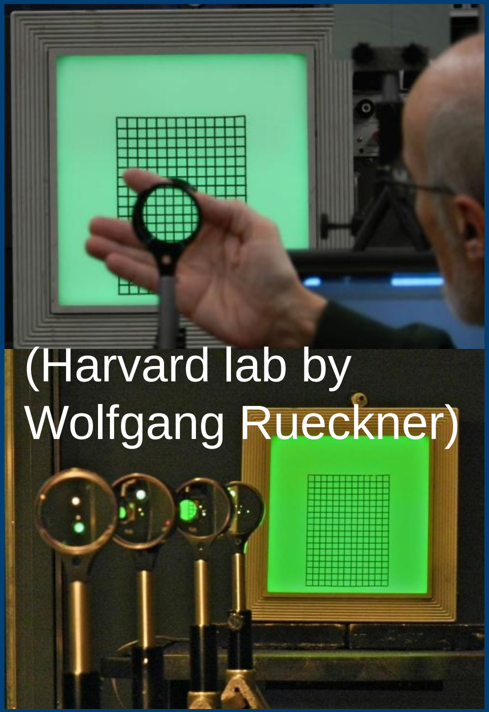
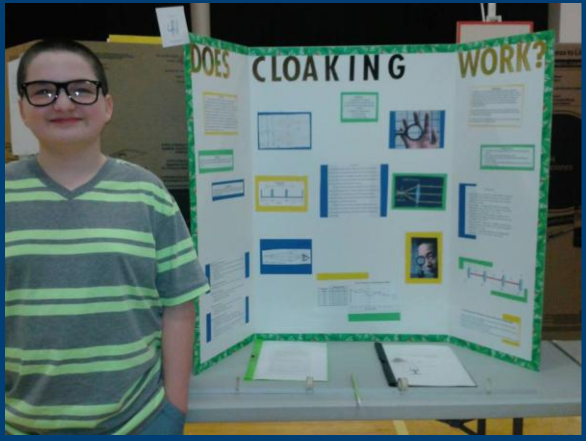
(Photos by J. Adam Fenster / University of Rochester)



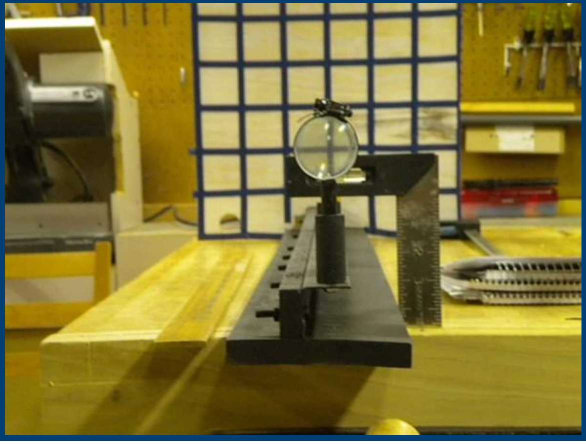


(Harvard lab by Wolfgang Rueckner)

Joshua G. (7th grade)



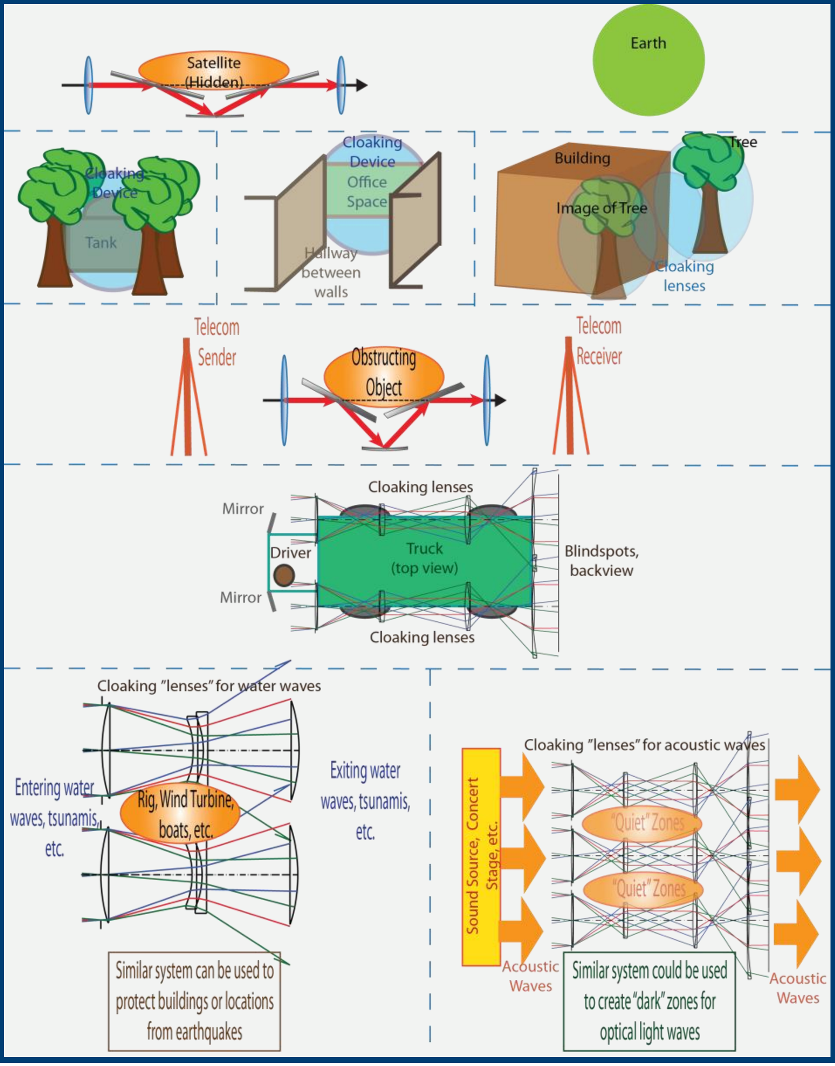
Joel & Linda D.



Josh O. (8th grade)

Possible Applications

- Some ideas
- Practical uses likely from: The public, designers, entrepreneurs, industry, artists, engineers, etc.



(U.S. patent filed (2015))