Magnifying Metamaterial Lens Design by Coordinate Transformation

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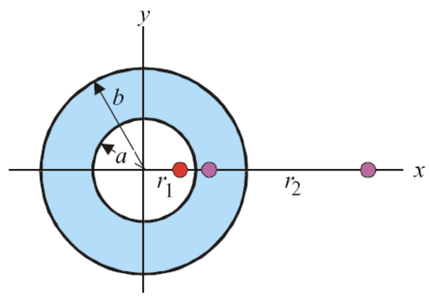
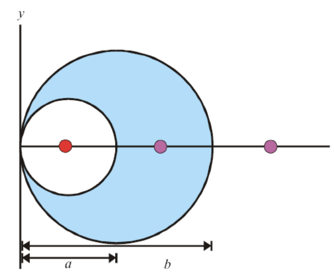
Outline

- Prior Work on Magnifying Metamaterial Lens
- Coordinate Transformation Properties of Maxwell Equations
- Magnifying Perfect Lens Design
- Impedance Matching in Magnifying Superlens
- Publications:
  - Tsang and Psaltis, arXiv:0708.0262 (Aug 2, 2007)
  - Tsang and Psaltis, Phys. Rev. B **77**, 035122 (Jan 2008)
- Relevant work:
  - Kildishev and Narimanov, arXiv:0708.3798 (Aug 28, 2007); Opt. Lett. **32**, 3432 (Dec 2007)
  - Kildishev and Shalaev, arXiv:0711.0183 (Nov 1, 2007); Opt. Lett. **33**, 43 (Jan 2008)

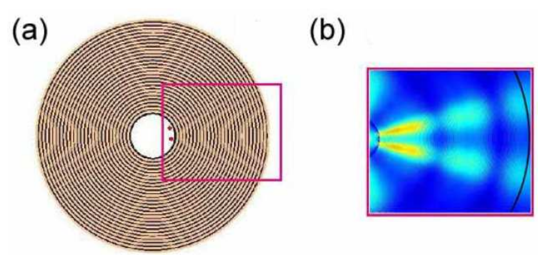
Magnifying Metamaterial Lenses

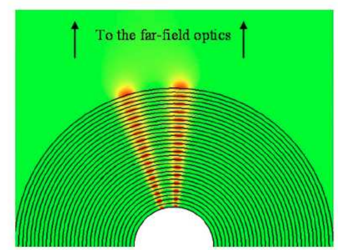
- Pendry, Opt. Express **11**, 755 (2003):



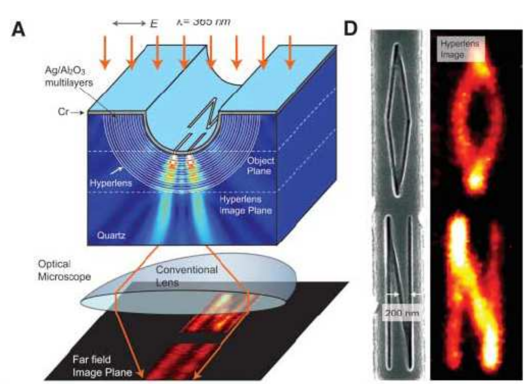


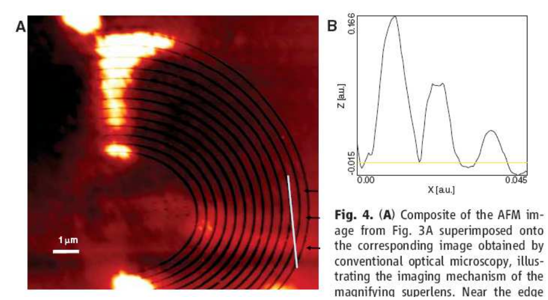
- Jacob, Alekseyev, and Narimanov, Opt. Express **14**, 8247 (2006): Salandrino and Engheta, Phys. Rev. B **74**, 075103 (2006):





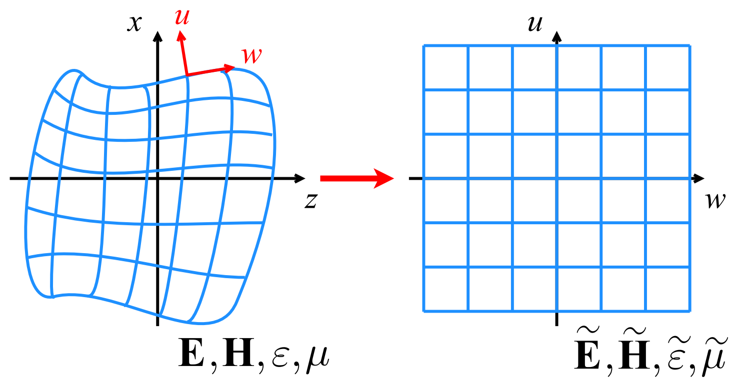
- Liu *et al.*, Science **315**, 1686 (2007): Smolyaninov, Hung, and Davis Science **315**, 1699 (2007):





Transformation Optics

- Leonhardt, Science **312**, 1777 (2006); Pendry, Schurig, and Smith, Science **312**, 1780 (2006)



- For orthogonal coordinates, and ε and μ diagonal in the (u, v, w) coordinate system,

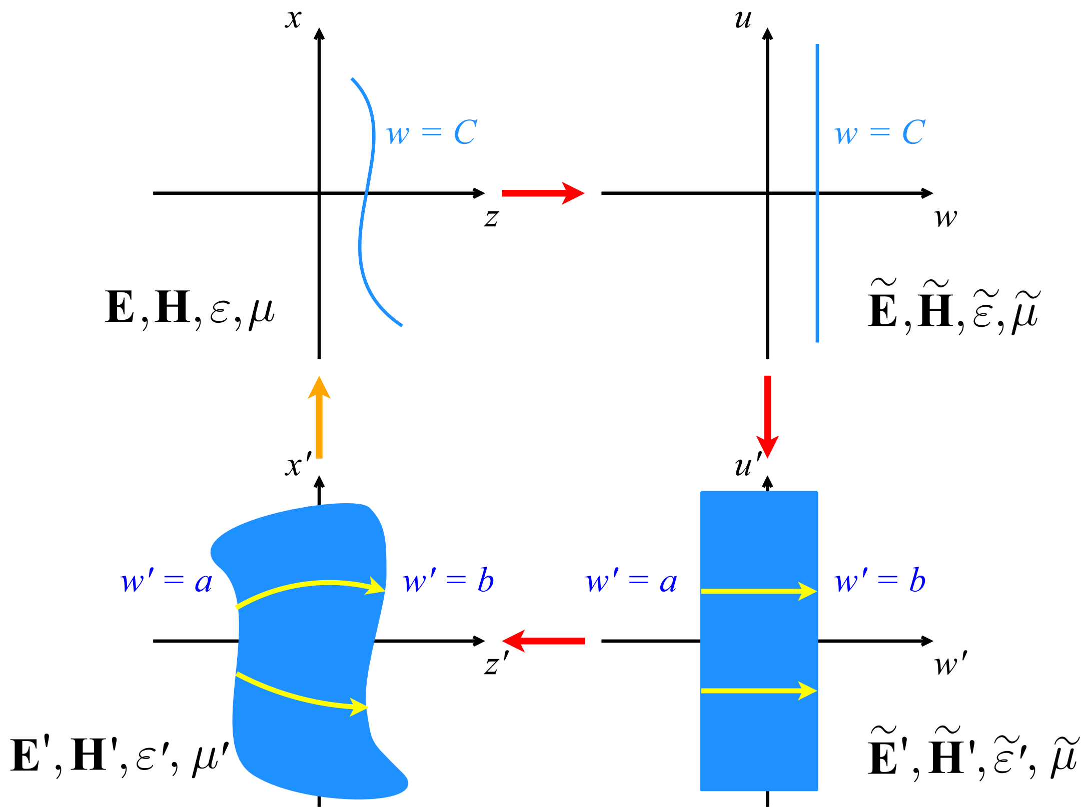
$$h_u = \sqrt{\left(\frac{\partial x}{\partial u}\right)^2 + \left(\frac{\partial y}{\partial u}\right)^2 + \left(\frac{\partial z}{\partial u}\right)^2}, \quad \text{etc.}$$

$$\tilde{E}_u = h_u E_u, \quad \tilde{H}_u = h_u H_u, \quad \tilde{\varepsilon}_u = \frac{h_u h_v h_w}{h_u^2}\varepsilon_u, \quad \tilde{\mu}_u = \frac{h_u h_v h_w}{h_u^2}\mu_u, \quad \text{etc.}$$

$$\tilde{\nabla} \cdot (\tilde{\varepsilon}\tilde{\mathbf{E}}) = 0, \quad \tilde{\nabla} \cdot (\tilde{\mu}\tilde{\mathbf{H}}) = 0, \quad \tilde{\nabla} \times \tilde{\mathbf{E}} = i\omega\mu_0\tilde{\mu}\tilde{\mathbf{H}}, \quad \tilde{\nabla} \times \tilde{\mathbf{H}} = -i\omega\varepsilon_0\tilde{\varepsilon}\tilde{\mathbf{E}} \qquad (1)$$

- $\tilde{\mathbf{E}}$, $\tilde{\mathbf{H}}$, $\tilde{\varepsilon}$, and $\tilde{\mu}$ see (u, v, w) as a Cartesian coordinate system

Simple Perfect Lens Design

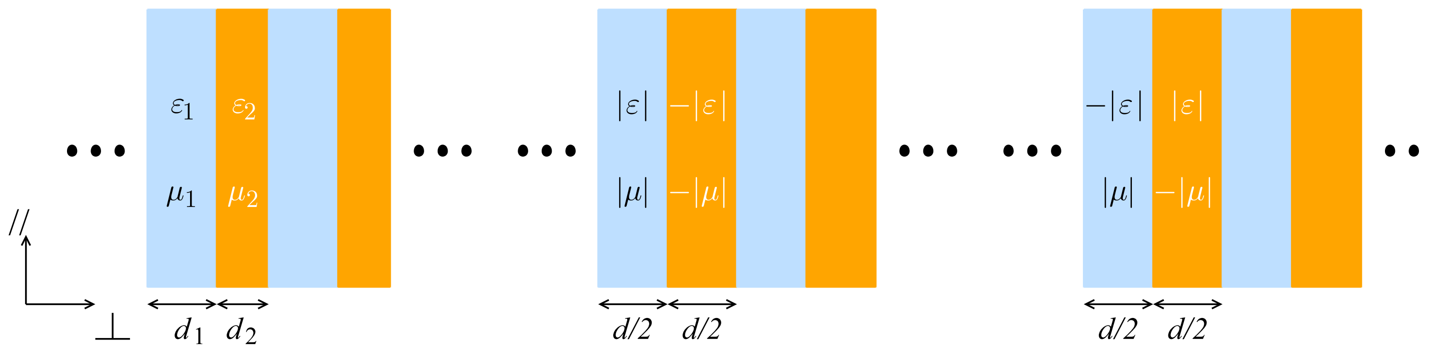


- Simple mapping:

$$u(u', v', w') = u', \quad v(u', v', w') = v', \quad w(u', v', w') = C \text{ for } a \leq w' \leq b.$$

- Zero transverse material constants ($\varepsilon'_u = \varepsilon'_v = \mu'_u = \mu'_v = 0$) and infinite longitudinal constants ($\varepsilon'_w = \mu'_w = \infty$)

Effective Medium



- effective medium theory:

$$\varepsilon_u = \varepsilon_v = \frac{\varepsilon_1 d_1 + \varepsilon_2 d_2}{d_1 + d_2}, \qquad \varepsilon_w = \frac{d_1 + d_2}{d_1/\varepsilon_1 + d_2/\varepsilon_2},$$

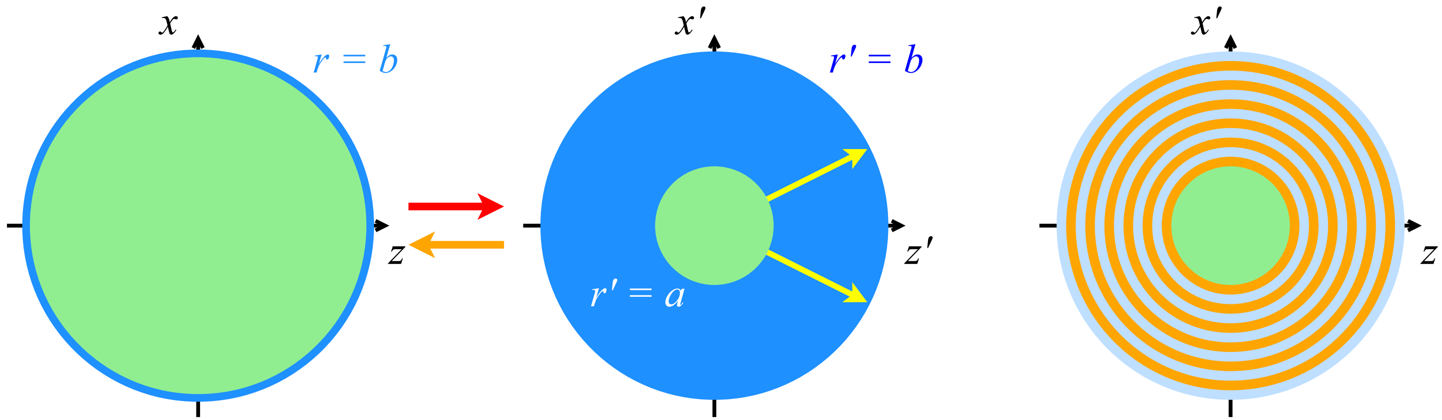
$$\mu_u = \mu_v = \frac{\mu_1 d_1 + \mu_2 d_2}{d_1 + d_2}, \qquad \mu_w = \frac{d_1 + d_2}{d_1/\mu_1 + d_2/\mu_2}.$$

- Make $d_1 = d_2$, $\varepsilon_1 = -\varepsilon_2$, $\mu_1 = -\mu_2$,

$$\varepsilon_u = \varepsilon_v = 0, \qquad \varepsilon_w = \infty,$$

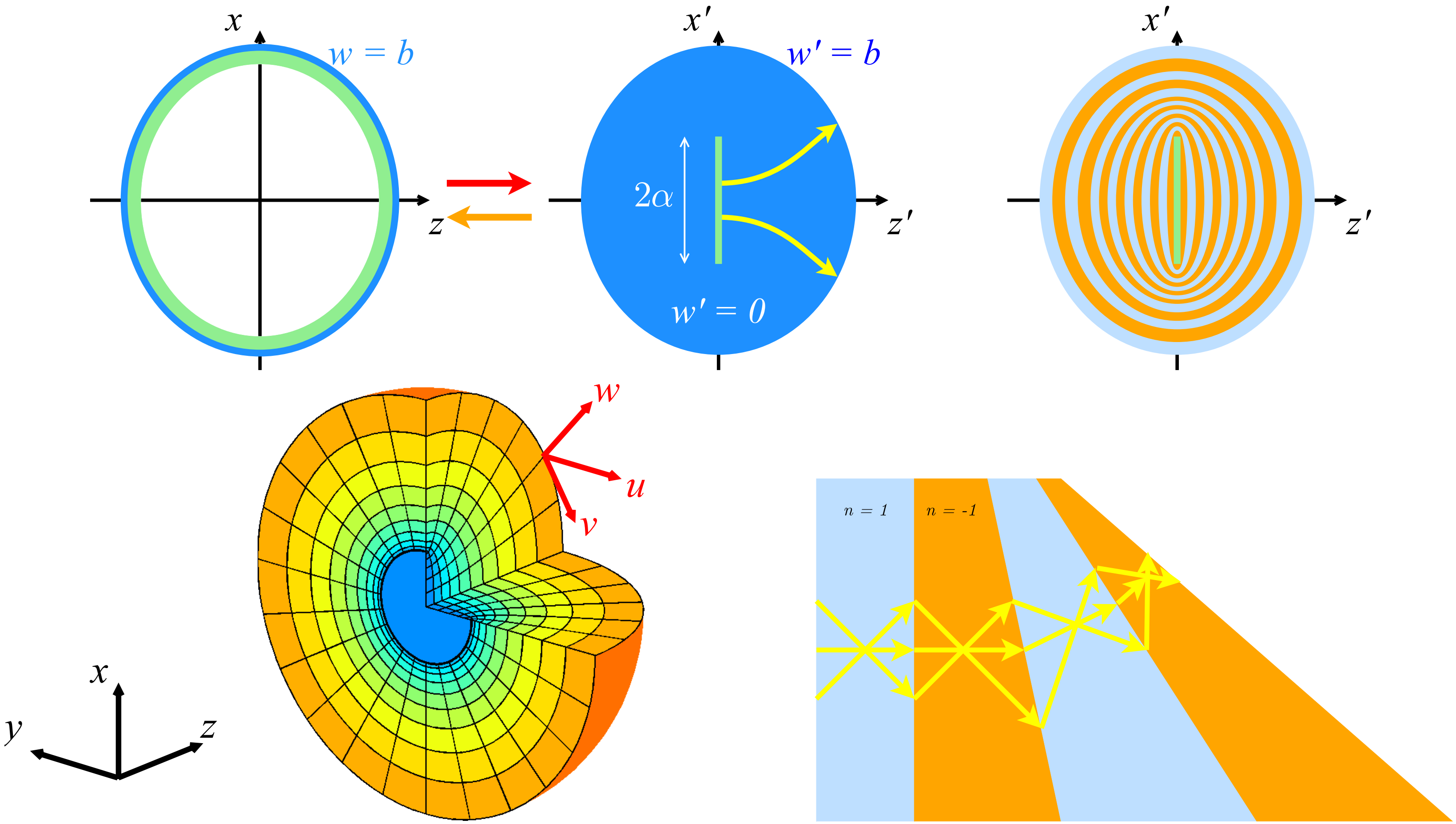
$$\mu_u = \mu_v = 0, \qquad \mu_w = \infty.$$

Spherical Perfect Lens



$$x = r\sin\theta\cos\phi, \quad y = r\sin\theta\sin\phi, \quad z = r\cos\theta.$$

Spheroidal Perfect Lens



$$x = \alpha \cosh w \cos v \cos u, \quad y = \alpha \cosh w \cos v \sin u, \quad z = \alpha \sinh w \sin v.$$

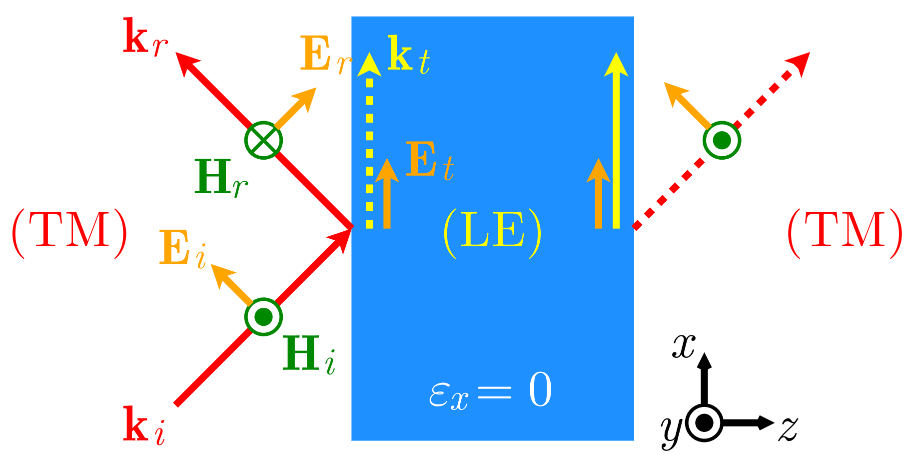
Oblate Spheroidal (Arfken, *Mathematical Methods for Physicists* (Academic, Orlando, 1970))

Impedance Matching for Plasmonic Lenses

- If we can't control μ, what is the optimal ε?
- Salandrino and Engheta, PRB **74**, 075103 (2006) suggests

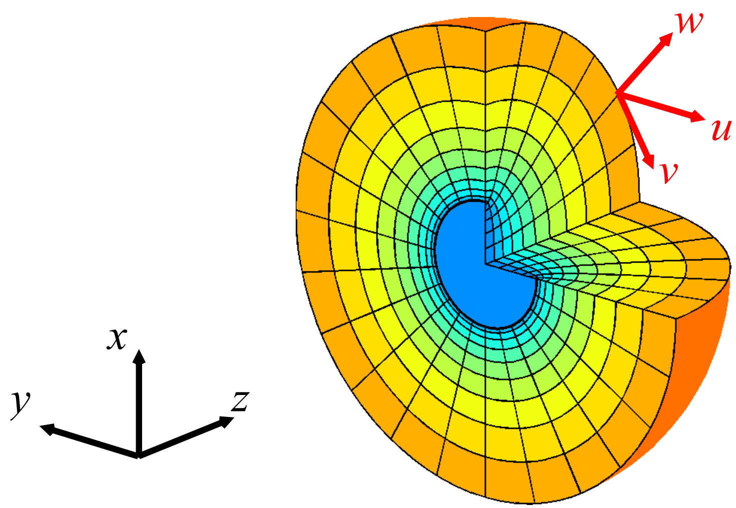
$$\varepsilon_u = \varepsilon_v = 0 \tag{2}$$

- TM waves propagate like rays inside lens, analogous to resonance cones
- But Maxwell's equations tell us that for $\varepsilon_u = \varepsilon_v = 0$, $\mathbf{H} = 0$, we have only quasi-electrostatic waves



- Solution: make $\varepsilon_u, \varepsilon_v \neq 0$, but $\varepsilon_w = \infty$, which gives TEM waves.
- Magnifying superlenses can be made in spherical or spheroidal geometry.

Conclusion



- Magnifying perfect lens design using coordinate transformation
- Magnifying superlens design
- Be careful with impedance matching
- Analysis assumes lossless media
- Tsang and Psaltis, Phys. Rev. B **77**, 035122 (2008)
- http://mankei.tsang.googlepages.com/