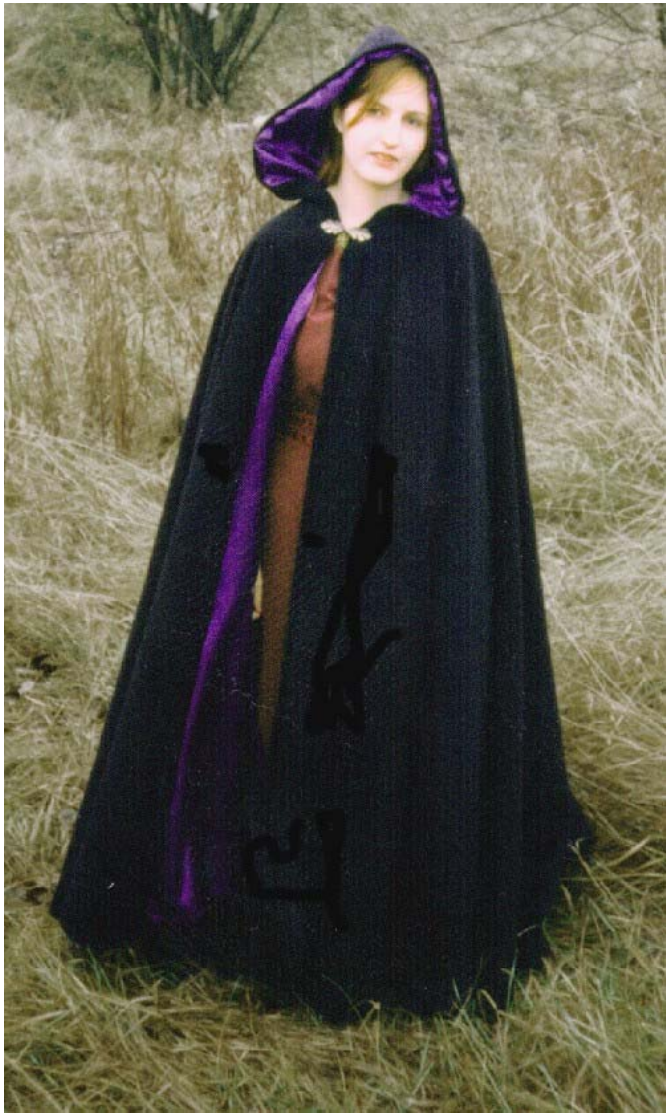
Helsinki University of Technology
SMARAD Centre of Excellence
Radio Laboratory

Alternative approaches to electromagnetic cloaking and invisibility

Sergei Tretyakov and colleagues

December 2007

What is a cloak?



Cloak (Lynoure Braakman , 230 €)

Invisibility cloak

The full circle cloak uses a large amount of fabric (roughtly 6 metres).
The amount of fabric makes it move nicely.
It also makes the cloak comfortably warm. The cloak can be worn on the body in different ways and
the hood ***can be used for different effects***.

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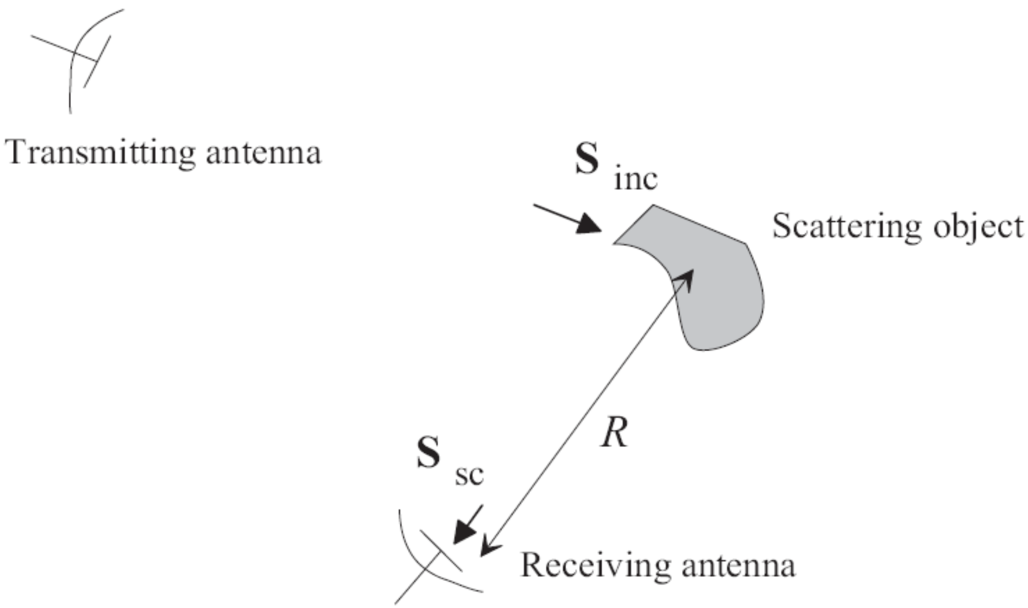
Scattering cross section and radar cross section

- Scattering cross section



$$\sigma = \lim_{R\to\infty} 4\pi R^2 \frac{S_{\mathrm{sc}}}{S_{\mathrm{inc}}} = \lim_{R\to\infty} 4\pi R^2 \frac{|E_{\mathrm{sc}}|^2}{|E_{\mathrm{inc}}|^2} = \lim_{R\to\infty} 4\pi R^2 \frac{|H_{\mathrm{sc}}|^2}{|H_{\mathrm{inc}}|^2}$$

Stealth technology

- Technology to minimize radar cross section (backscattering)

F-117

Total scattering cross section

- Differential cross section

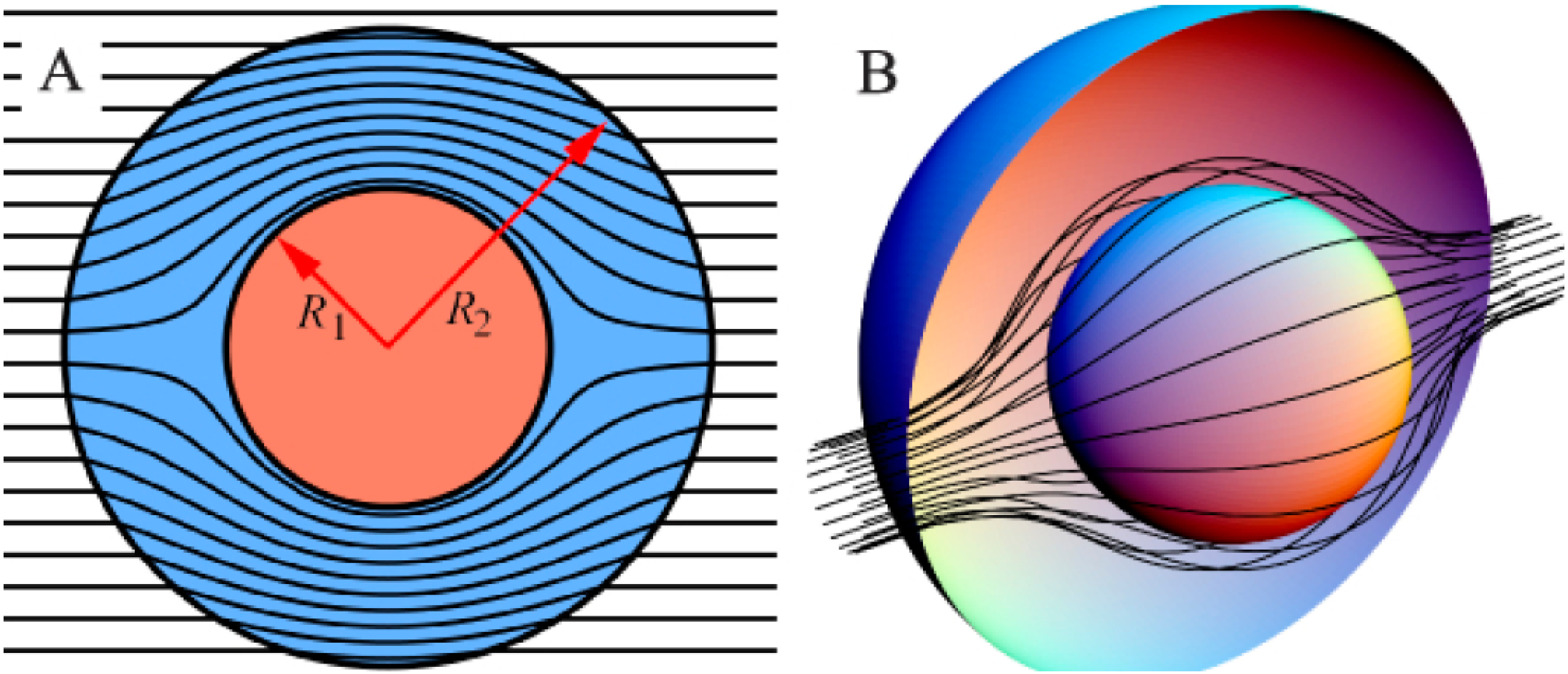
$$\sigma_{\mathrm{dif}} = \lim_{R \to \infty} R^2 \frac{S_{\mathrm{sc}}}{S_{\mathrm{inc}}}$$

- Total scattering cross section

$$\sigma_{\mathrm{tot}} = \int \sigma_{\mathrm{dif}} \, d\Omega = \frac{P_{\mathrm{sc}}}{S_{\mathrm{inc}}}$$

Cloaking technology

- Technology to minimize *total* scattering section of objects, for arbitrary illumination



www.sciencexpress.org / 25 May 2006

Role of the media

Telegraph.co.uk

Professor John Pendry, from Imperial College London,
said that it may not take long to develop an invisible fabric…
"If there is adequate funding,
I'd have thought it would take in the order of five years," he said.

"The cloak would act like you've opened a hole in space," said Prof Smith.

"You may wish to put a cloak over the refinery that is blocking your view of the bay," Duke University's David Schurig, another of Pendry's co-authors, was quoted as saying.

Pendry-Schurig-Smith cloak

- Space transformation, making a ”hole in space”:

$$r' = R_1 + r\left(R_2 - R_1\right)/R_2$$
$$\theta' = \theta,$$
$$\phi' = \phi$$

the region $0<r'<R_1$ ”does not exist”!

- Material parameters transform:

$$\varepsilon'_{r'} = \mu'_{r'} = \frac{R_2}{R_2 - R_1}\frac{\left(r' - R_1\right)^2}{r'^2}$$
$$\varepsilon'_{\theta'} = \mu'_{\theta'} = \frac{R_2}{R_2 - R_1},$$
$$\varepsilon'_{\phi'} = \mu'_{\phi'} = \frac{R_2}{R_2 - R_1}$$

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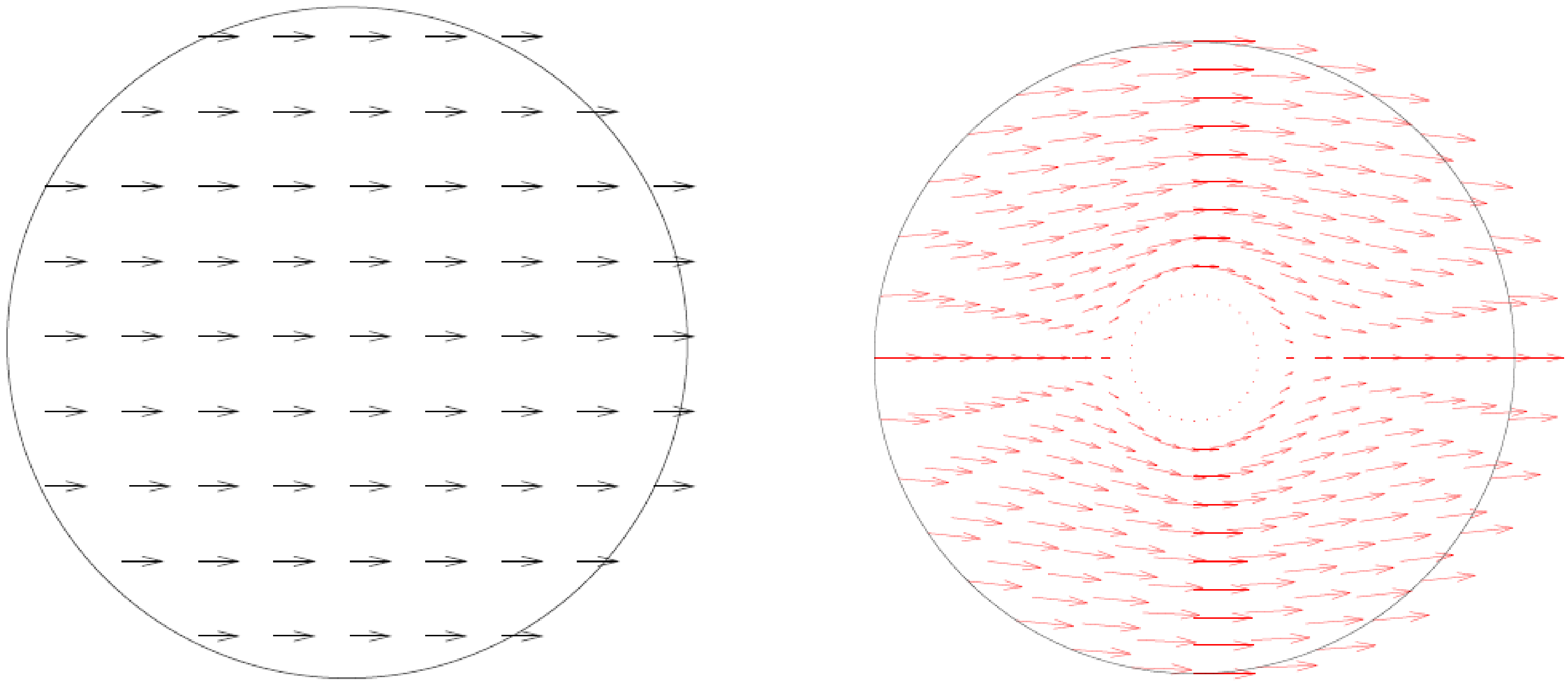
Earlier work

- Inverse problems for conductivity distributions



A. Greenleaf, M. Lassas, G. Uhlmann, Anisotropic conductivities that cannot be detected by EIT, *Physiological Measurement*, 24(2003), 413-420.

A. Greenleaf, M. Lassas, G. Uhlmann, On non-uniqueness for Calderon's inverse Problem, *Mathematical Research Letters*, 10(2003), 685-693.

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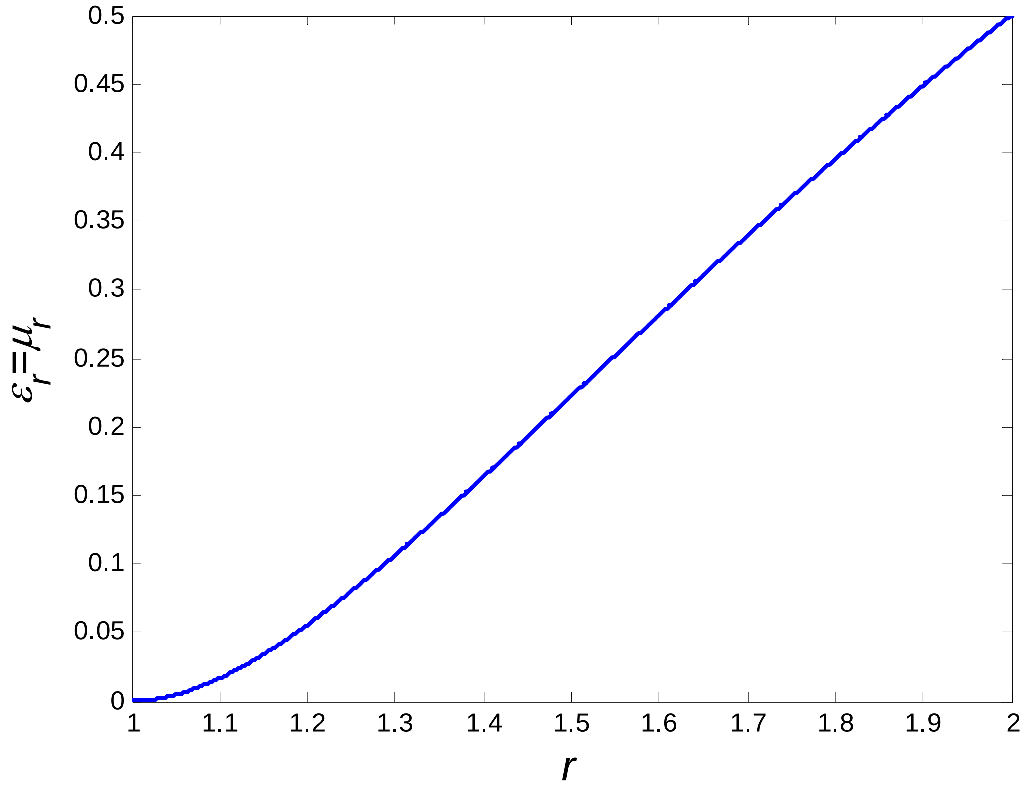
Role of the electromagnetic media

- R_1=1 m; R_2=2 m



$$\epsilon_\theta = \epsilon_\phi = 2$$

$$\mu_\theta = \mu_\phi = 2$$

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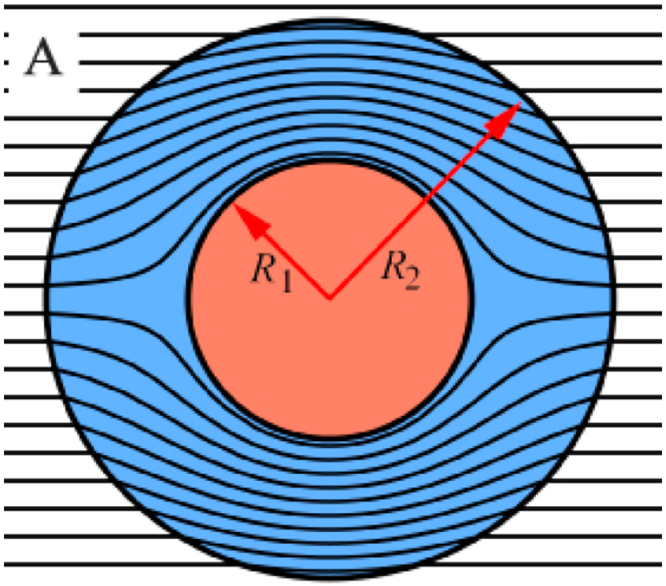
Fundamental difficulties

- Waves must travel faster than light



- Perfectly-matched-layer conditions must be satisfied at the surface:

$$\epsilon_r = \frac{1}{\mu_\theta} = \frac{1}{\mu_\phi} \qquad \mu_r = \frac{1}{\epsilon_\theta} = \frac{1}{\epsilon_\phi}$$

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Fundamental difficulties

- Fields may vary fast close to the inner boundary: impossible to homogenize the composite (M. Lassas et al.)

- Fields at the inner boundry may blow up (M. Lassas et al.)

  Solution:

  When cloaking active objects in a ball or any objects in a cylinder, we have to use a PEC lining or a Soft-and-Hard lining.

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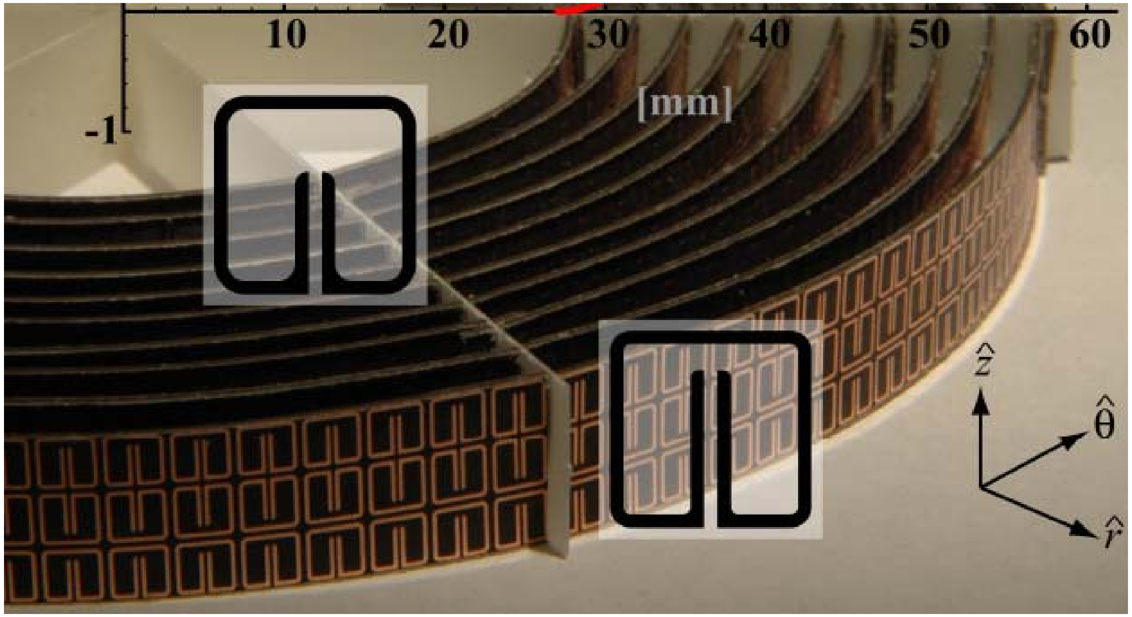
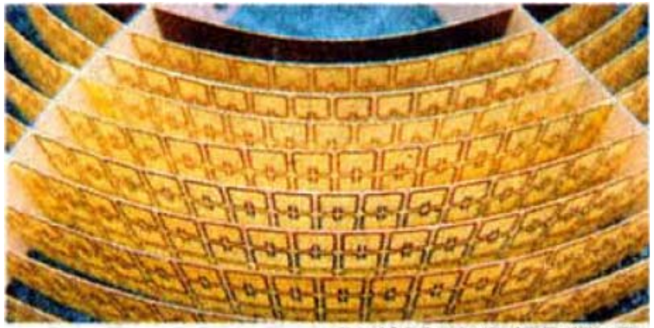
First step towards realization



www.sciencexpress.org / 19 October 2006



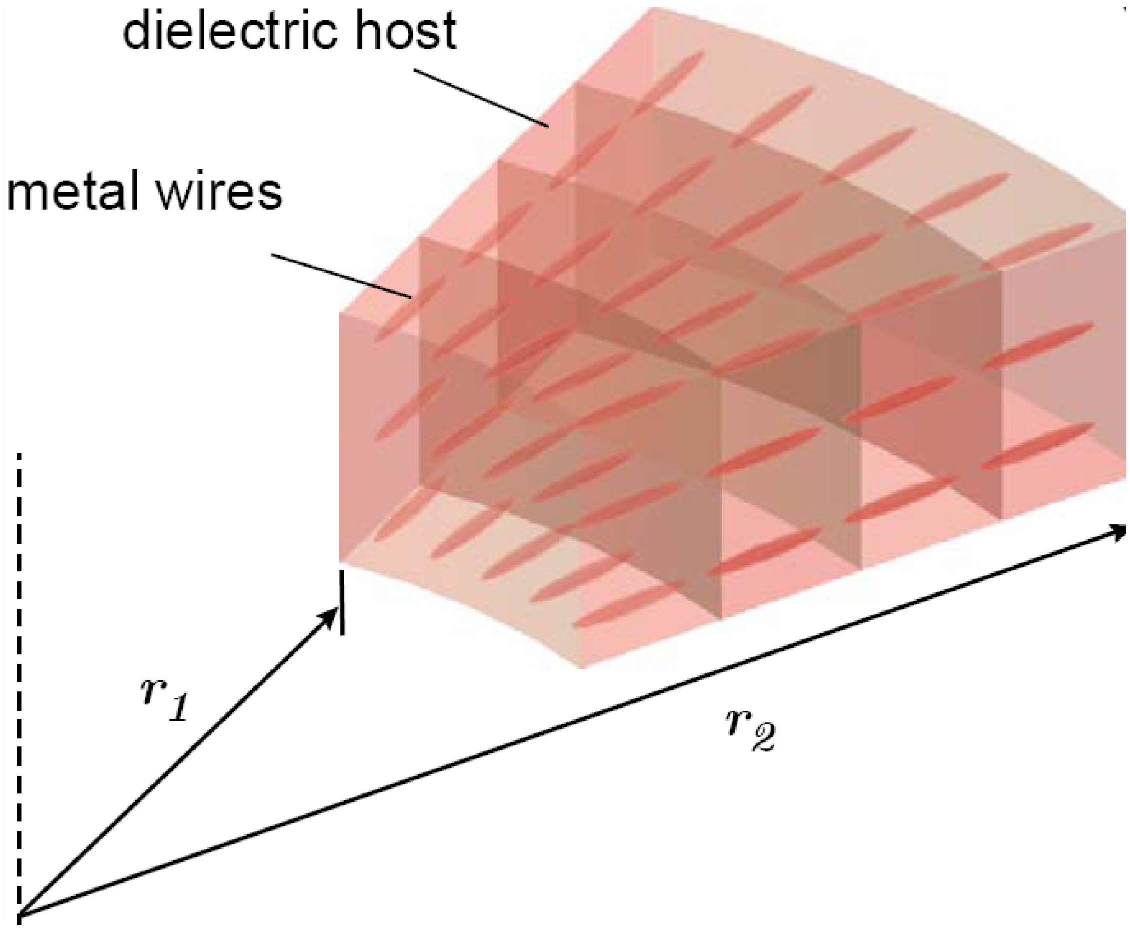
David Schurig/Duke University

NOW YOU SEE IT Duke researchers built a simplified version of their cloaking device out of copper rings and wires patterned onto fiber-glass sheets and demonstrated that it successfully diverted microwaves.

Science Times section of the New York Times

Works for E_z-H_θ polarization

Dual design

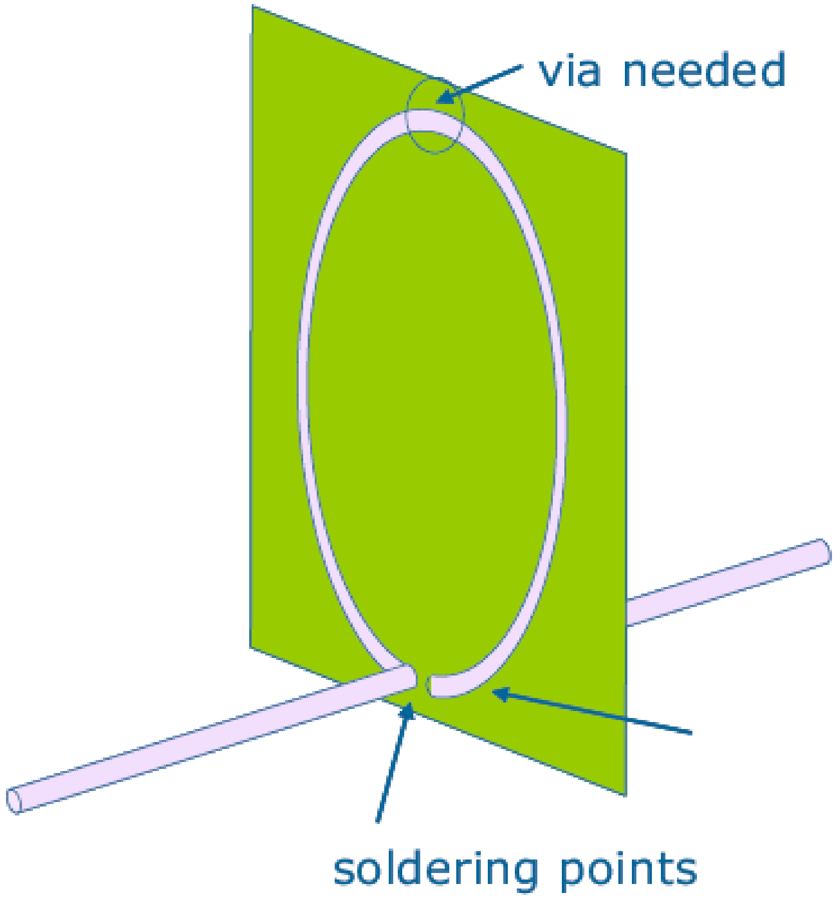


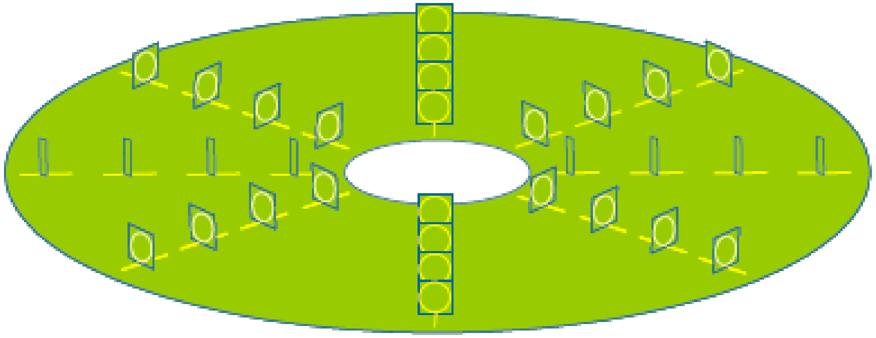
Wenshan Cai, et al., Optical cloaking with metamaterials, *Nature Photonics*, April 2007

Works for E_θ -H_z polarization

Dual-polarization design

- TKK, spring 2007, student assignment

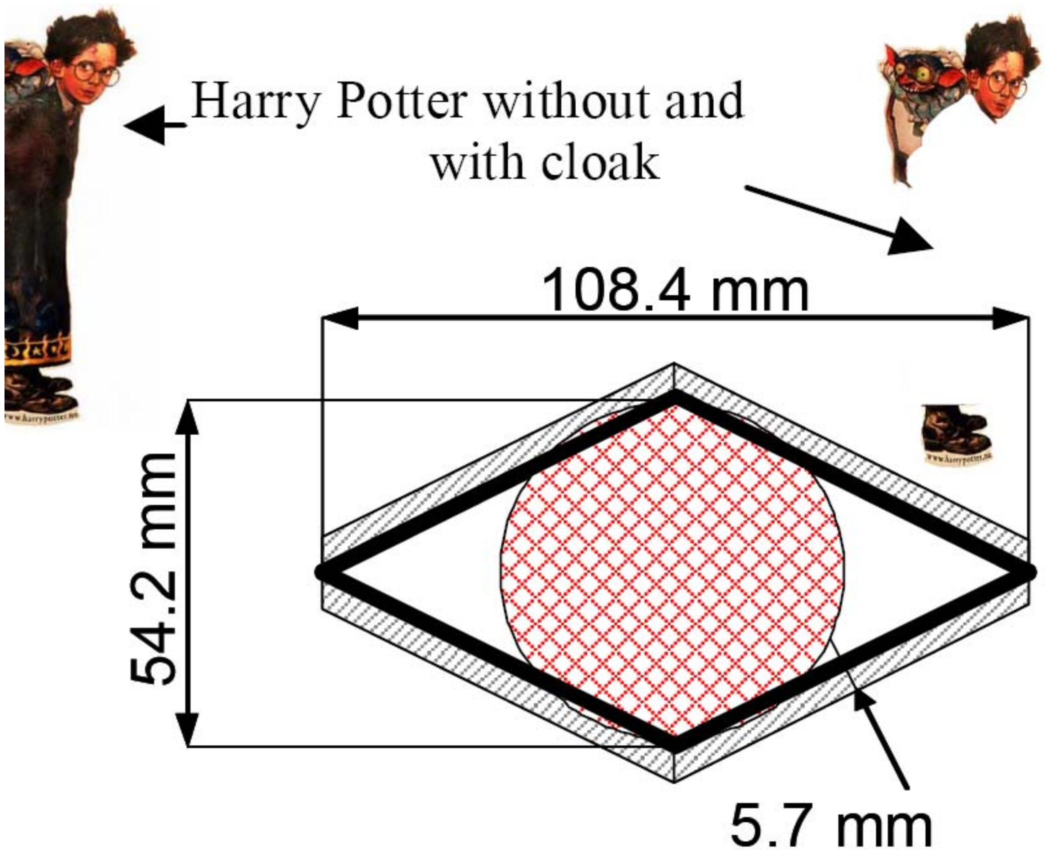




Works for both polarizations

Guiding waves around an object

- Using soft- and hard surfaces (P.-S. Kildal)



P.-S. Kildal, A. Kishk, Z. Sipus, RF invisibility using metamaterials:
Harry Potter's cloak or the emperor's new clothes?, *IEEE AP-S Symposium*, Honolulu, 2007.

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 44, NO. 11, NOVEMBER 1996

Comparison table by P.-S. Kildal

Cloaking method	Radially graded metamaterial		Geometry shaping and hard surface	
Required cross section	Circular cross section		Oblong cross section	
Theoretical basis (limitation of concept)	HF propagation (2a>λ)		LF scattering (2a<λ)	
Other limitations	Very thick and complex cloak		Angle of arrival must be known	
Metamaterial or metasurface needed	Anisotropic material		Anisotropic surface	
	TE case	**TM case**	**TE case**	**TM case**
Special material requirements	Anisotropic ε_r<1	Anisotropic η_r<1	PEC	PMC
Demonstrated to work in theory	Yes	Yes	Yes	Yes
Realizations	Not known	e.g. split ring resonators	metal	e.g. dielectric coating
Demonstrated to work in practice	No	No	Yes	Yes
Bandwidth	No work done yet	determined by metamaterial realization, meaning very narrow band	very wide	typical 20%, depends on size
Combined TE & TM theoretical case	Very complex anisotropy		PEC/PMC strip grids, i.e. ideal hard surface for dual polarization	
Combined TE & TM realization	Doubtful if at all possible		Metal strips on dielectric coating has almost same performance as TE and TM separate	

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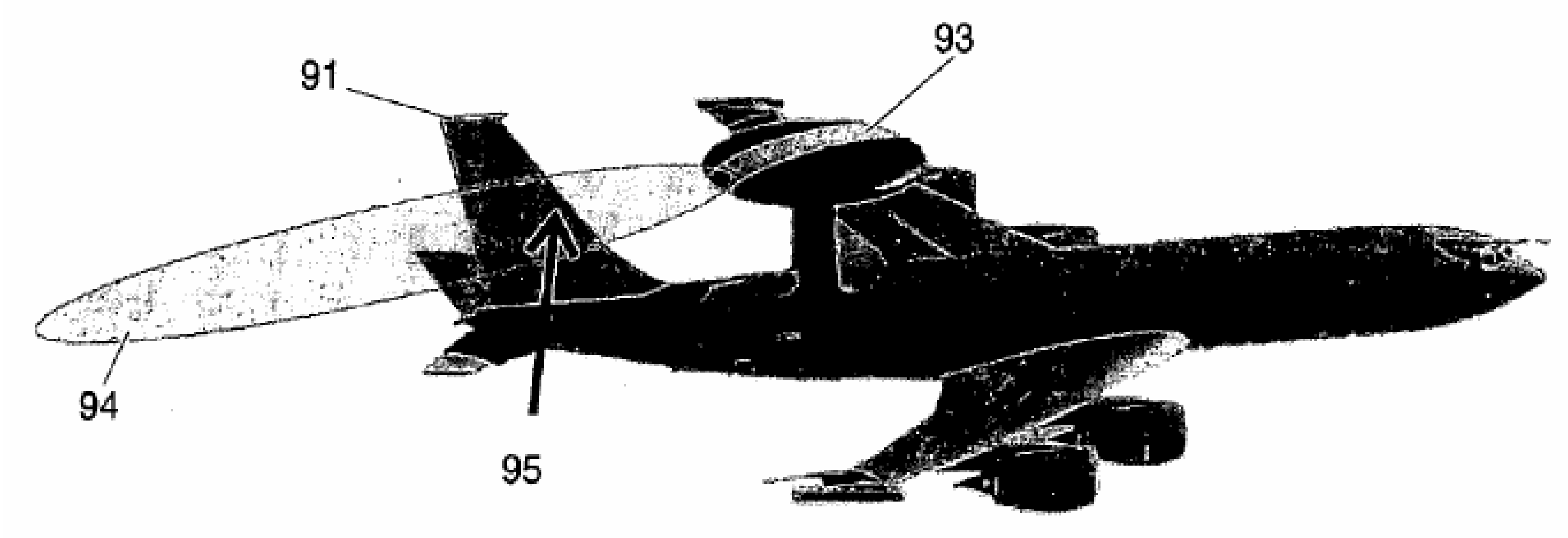
Sievenpiper et al. patent

- Priority of July 1, 2005



A tail 91 of an airplane may be covered by an artificial impedance structure 95 to allow the radar 93 to see through the tail 91.

Patent claim

1. A method for guiding waves over the surface of an object, said method comprising:

providing an impedance structure designed to guide an electromagnetic wave, the impedance structure having:

a dielectric layer having generally opposed first and second surfaces;

a conductive layer disposed on the first surface; and

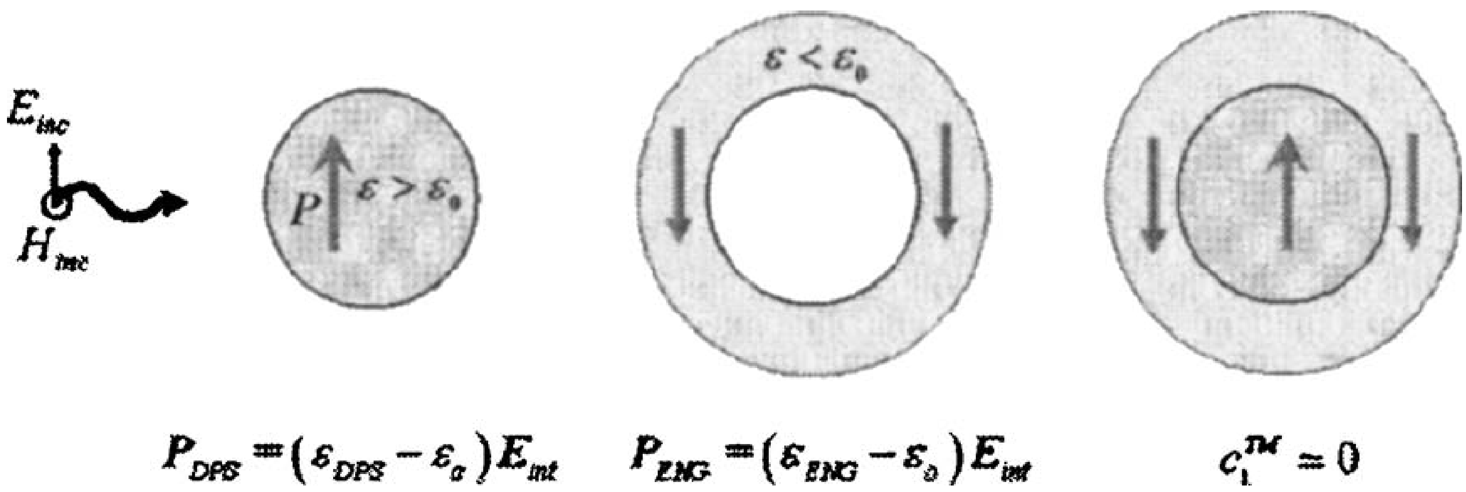
a plurality of conductive structures disposed on the second surface to provide a preselected impedance profile along the second surface;

covering said object with said impedance structure, wherein said impedance structure guides said electro-magnetic wave over the surface of said object.

Cloaking vs. Invisibility

- Cloak hides an ***arbitrary*** object (arbitrary to some extent)
- A ***certain*** object can be made ”hardly visible” by some other techniques

Compensation of the main-mode scattering:



A. Alu and N. Engheta, *Phys. Rev. E* 72, 016623 (2005)

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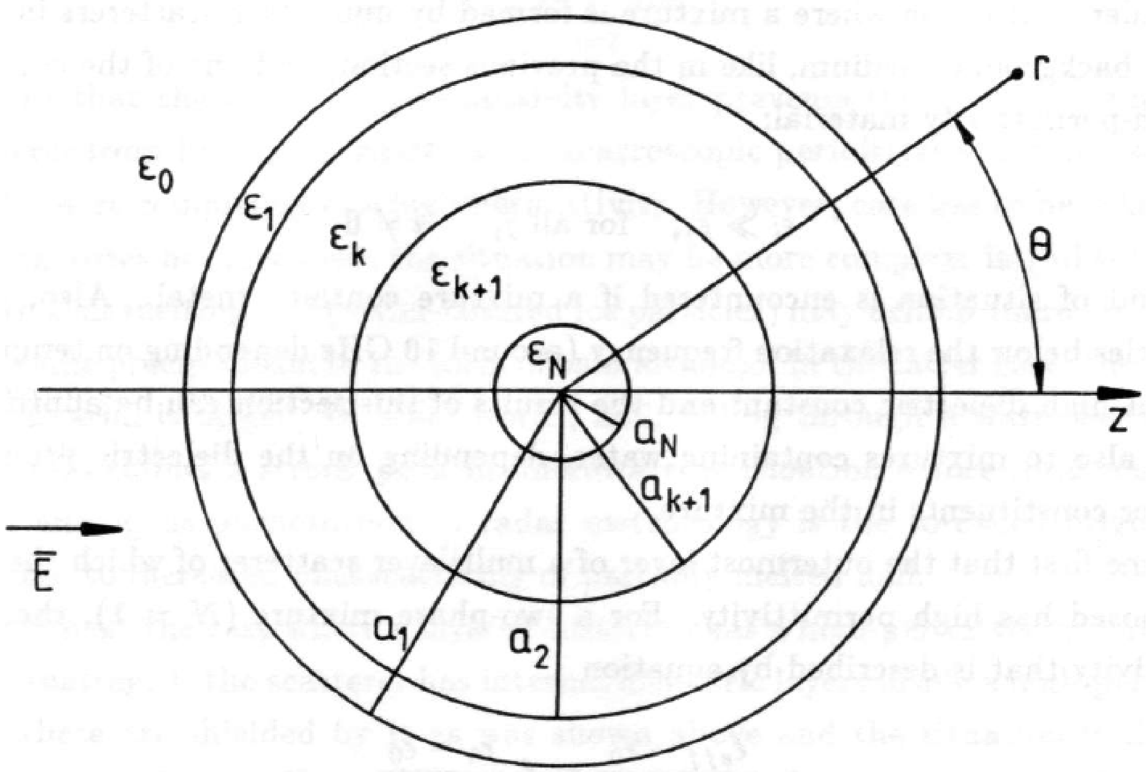
Layered spherical inclusions

- Are there invisible inclusions? - A. Sihvola, Properties of dielectric mixtures with layered spherical inclusions, *Microwave Radiom. Remote Sens. Appl.,* pp. 115-123, 1989



Invisible layered spherical inclusions

Dual-layer sperical inclusions. Radii $a_{1,2}$, counting from the center.

$$\epsilon_2 < 1, \qquad \epsilon_1 > 1$$

Invisibility condition:

$$(\epsilon_1 - 1)(\epsilon_2 + 2\epsilon_1) = \frac{a_2^3}{a_1^3}(\epsilon_1 - \epsilon_2)(1 + 2\epsilon_1)$$

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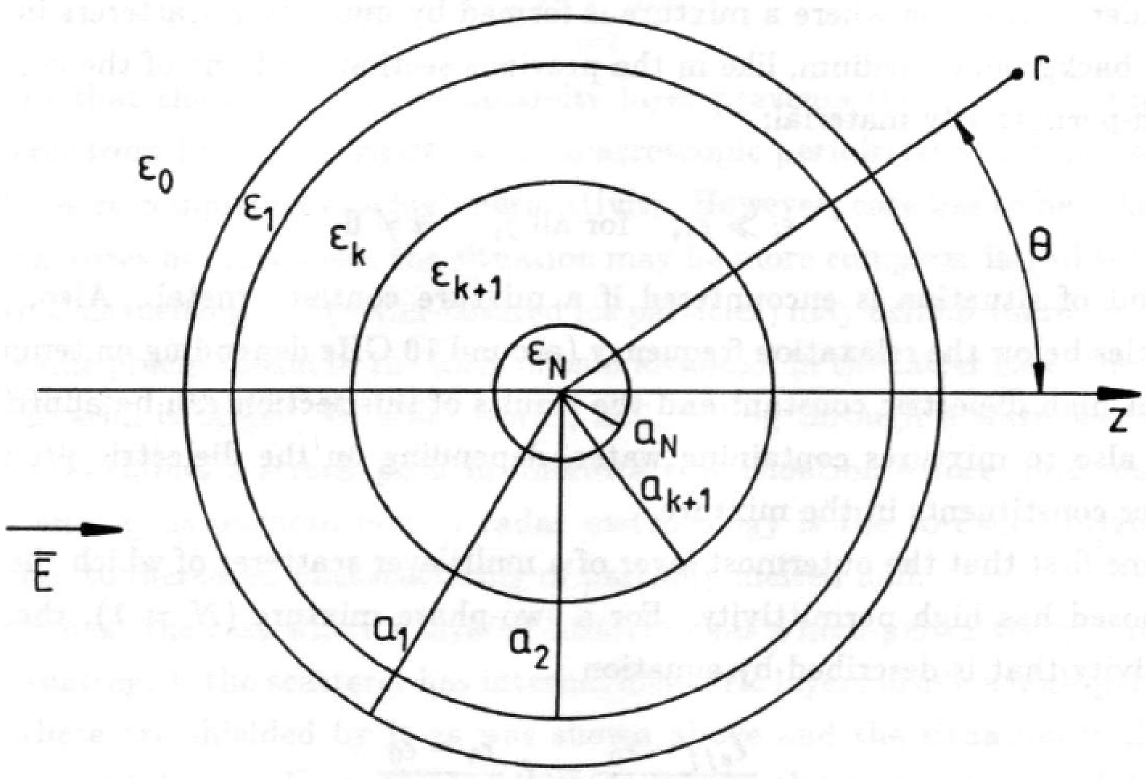
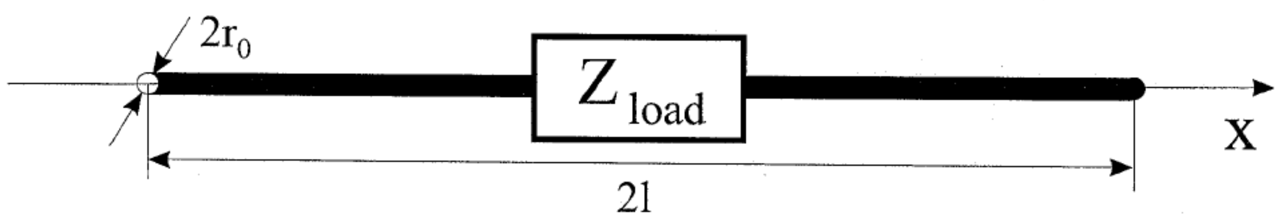
Similar technology for cloaking

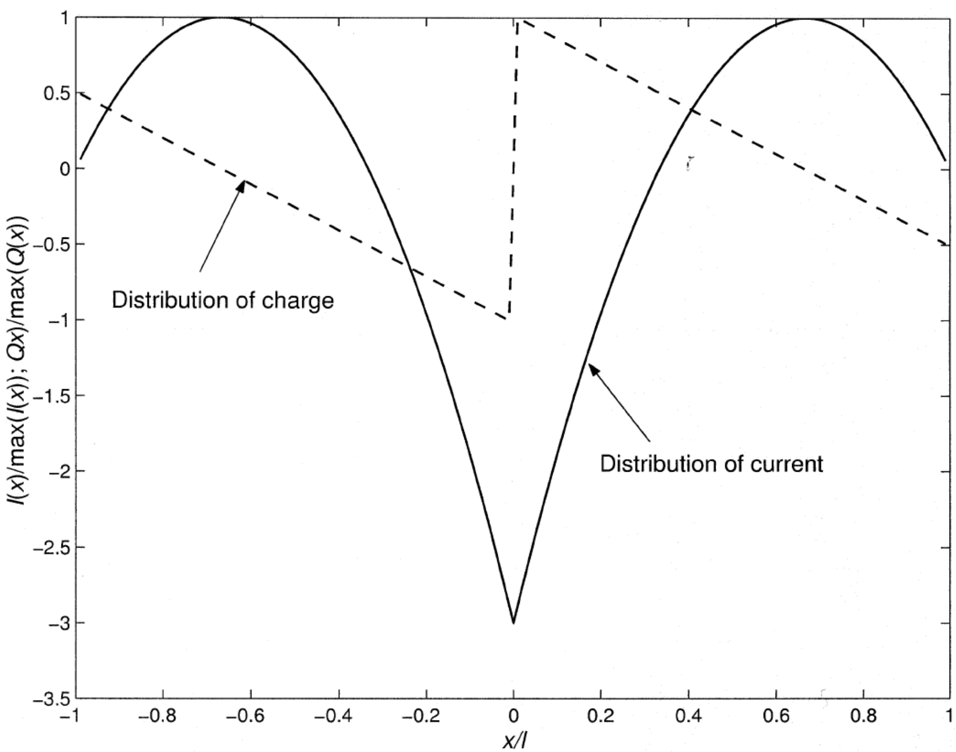
- The inner sphere can me made of an ideal conductor (N. Engheta)



Another way to compensate dipole scattering

- Loaded dipoles





The total induced dipole moment is zero, if

$$Z_{\mathrm{load}} = -4Z_{\mathrm{inp}}$$

S.A. Tretyakov, S.I. Maslovski, P.A. Belov, An analytical model of metamaterials based on loaded wire dipoles, *IEEE Trans. Antennas Propagation*, vol. 51, no. 10, pp. 2652-2658, 2003.

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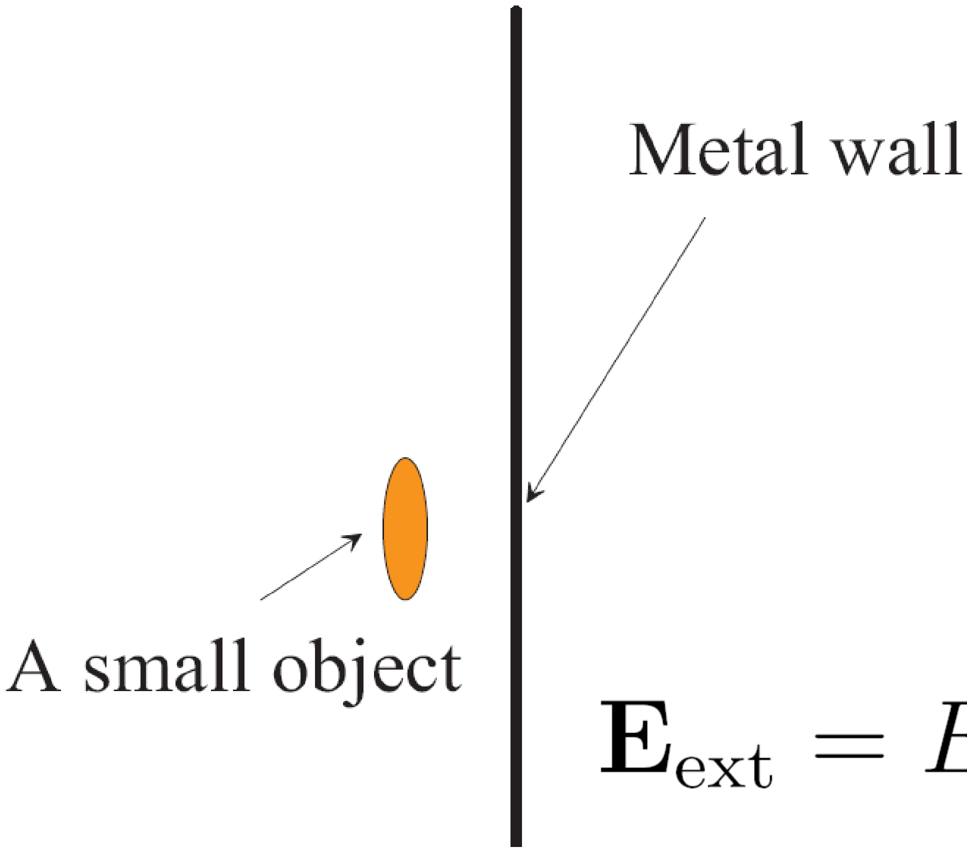
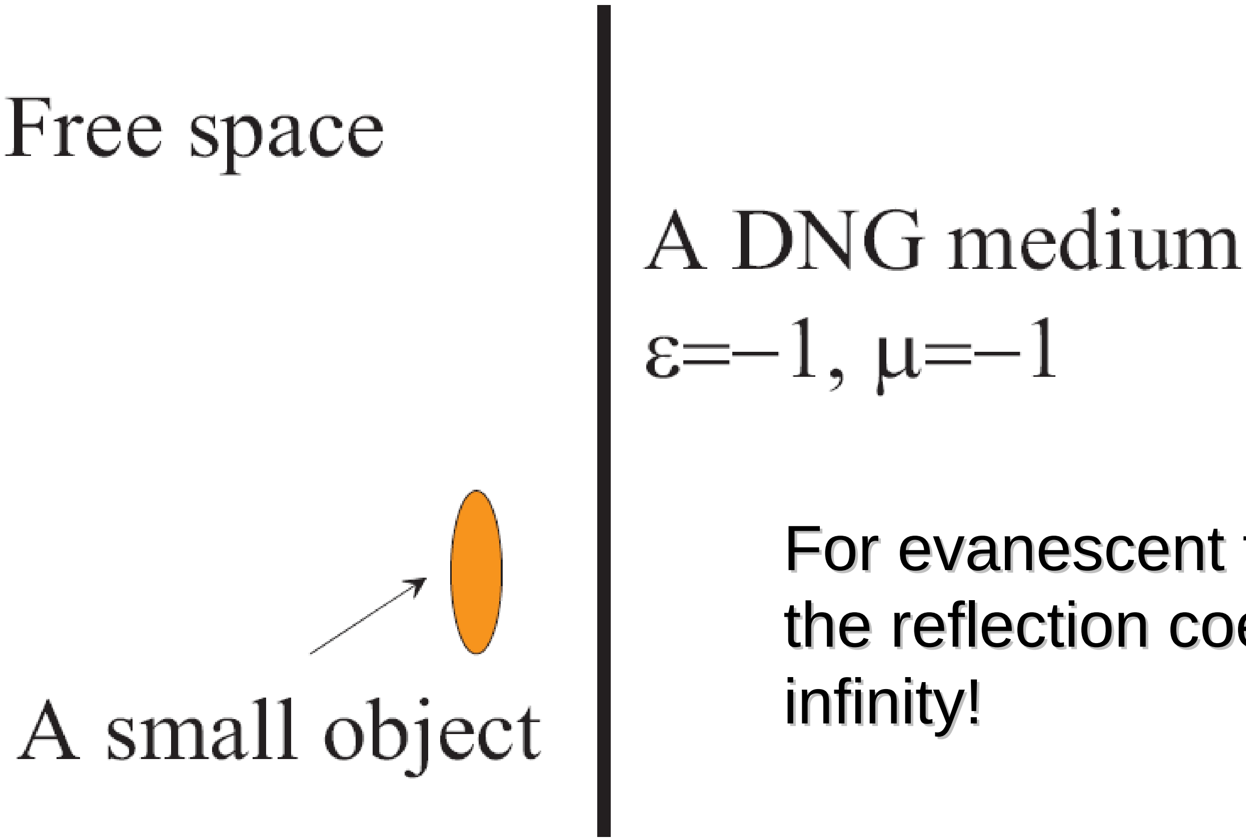
Compensation of excitation field



$$R \approx -1$$

$$\mathbf{E}_{\mathrm{ext}} = E_{\mathrm{inc}}(1 + R) \approx 0$$

”Shadowing” by resonant structures

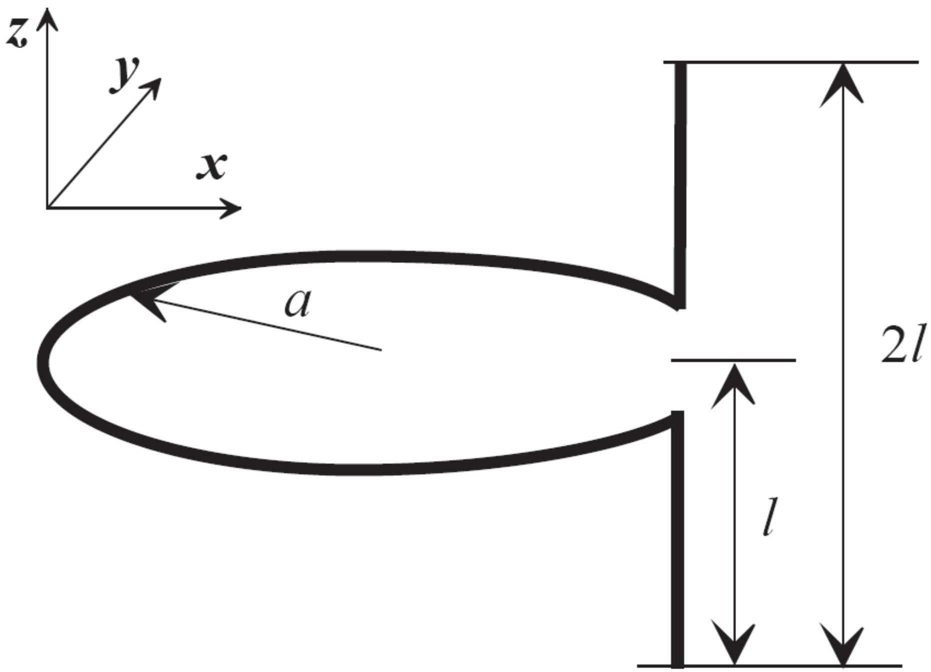


For evanescent field components the reflection coefficient tends to infinity!

Milton, Nicorovici, 2006: The same effect takes place in front of a perfect lens (?)

Compensation of induced EMF

- Or shaping the object:



``Invisibility´´ condition:

$$l = k_0 a(\pi a)$$

CP-incidence, wave along *y*:

$$\mathbf{E}_{\rm inc} = E_0(\mathbf{z}_0 \pm j\mathbf{x}_0)$$

$$\mathbf{H}_{\rm inc} = \frac{E_0}{\eta}(\mathbf{x}_0 \pm j\mathbf{z}_0)$$

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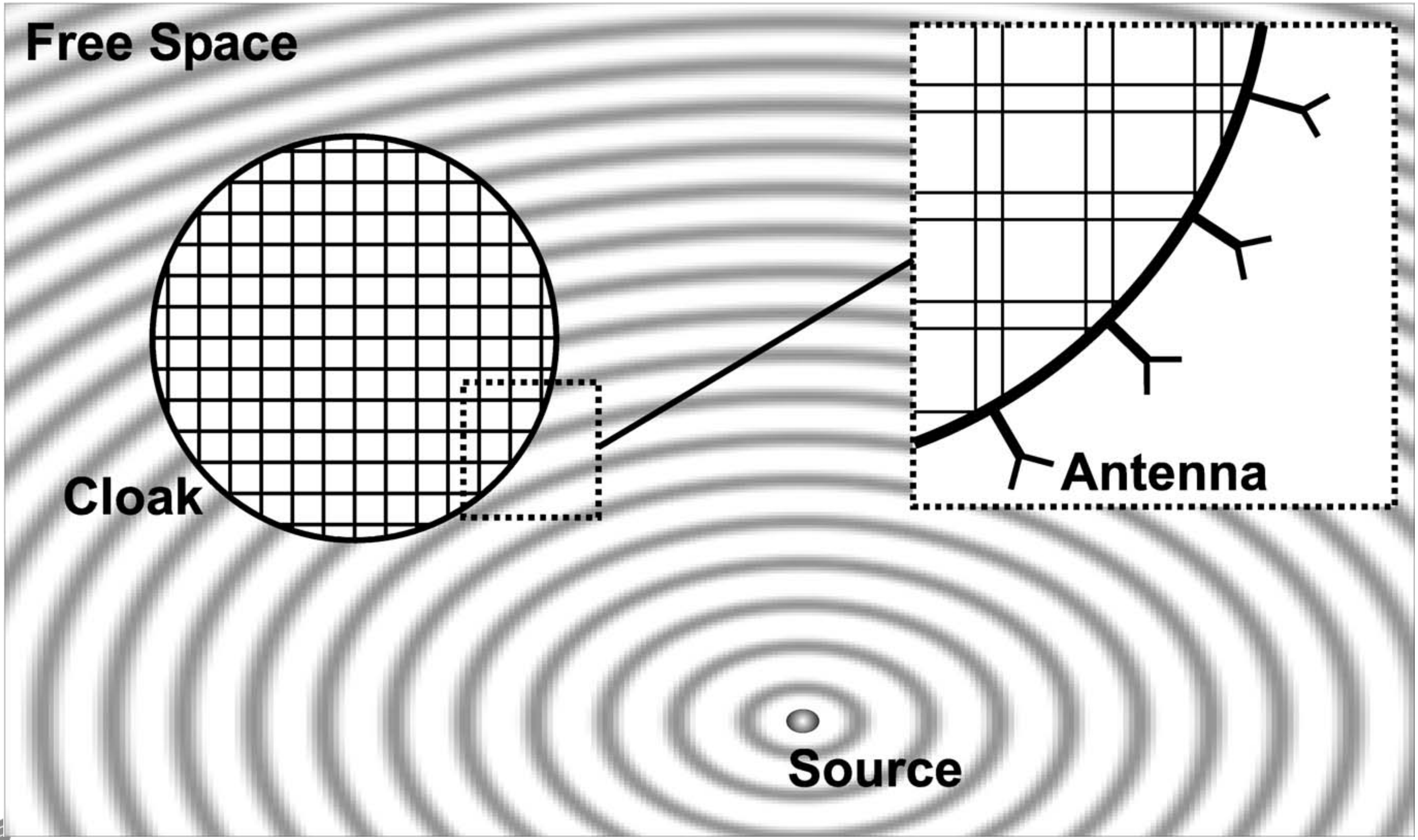
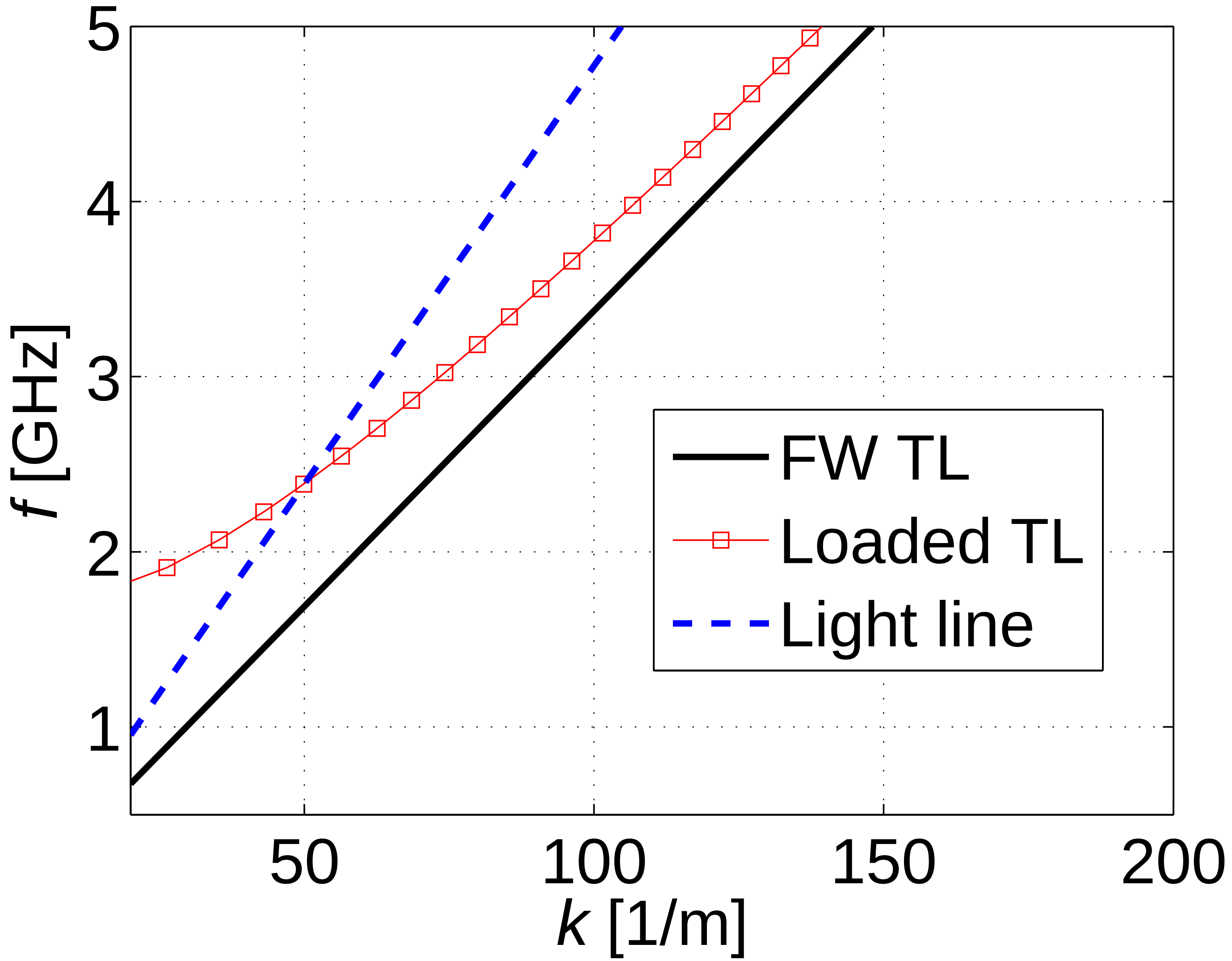
Transmission-line (TL) cloak

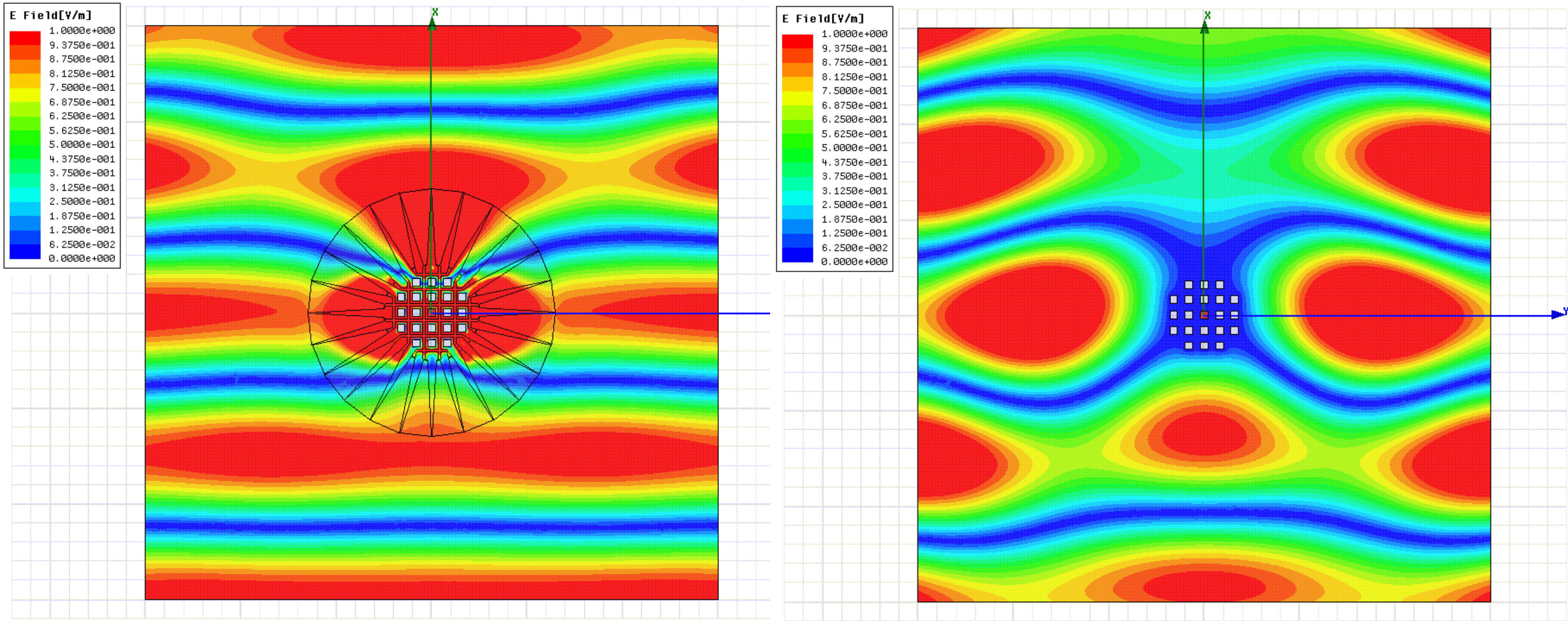
- TKK, spring 2007, student assignment



Dispersion inside the cloak



Cylindrical cloak



P. Alitalo, O. Luukkonen, L. Jylhä, J. Venermo, S.A. Tretyakov, Transmission-line networks cloaking objects from electromagnetic fields, to appear in *IEEE Trans. Antennas Propagation*.
Preprint at http://www.arxiv.org/abs/0706.4376