# Metamaterials: From Concepts to Applications

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**Manchester, England**

# Opening Statement

- Artificial materials
- Performance beyond limitations of conventional composites
- Low-dimensional metaparticles
- Periodic cellular architecture
- Maybe create optical magnetism

# Interesting area of research

$\varepsilon<0 \quad \mu<0$

↓

# Metamaterials

ε = permittivity, μ = permeability

# Basic Material Categories

$$n = \pm\sqrt{\varepsilon\mu}$$

**OR**

$$n = \pm\sqrt{(-\varepsilon)(-\mu)}$$

| | |
|---|---|
| **+ε, -μ**<br>Plasmas | **+ε, +μ**<br>Dielectrics |
| **-ε, -μ**<br>Artificial | **-ε, +μ**<br>Gyrotropic magnetic materials |

ABSORPTION

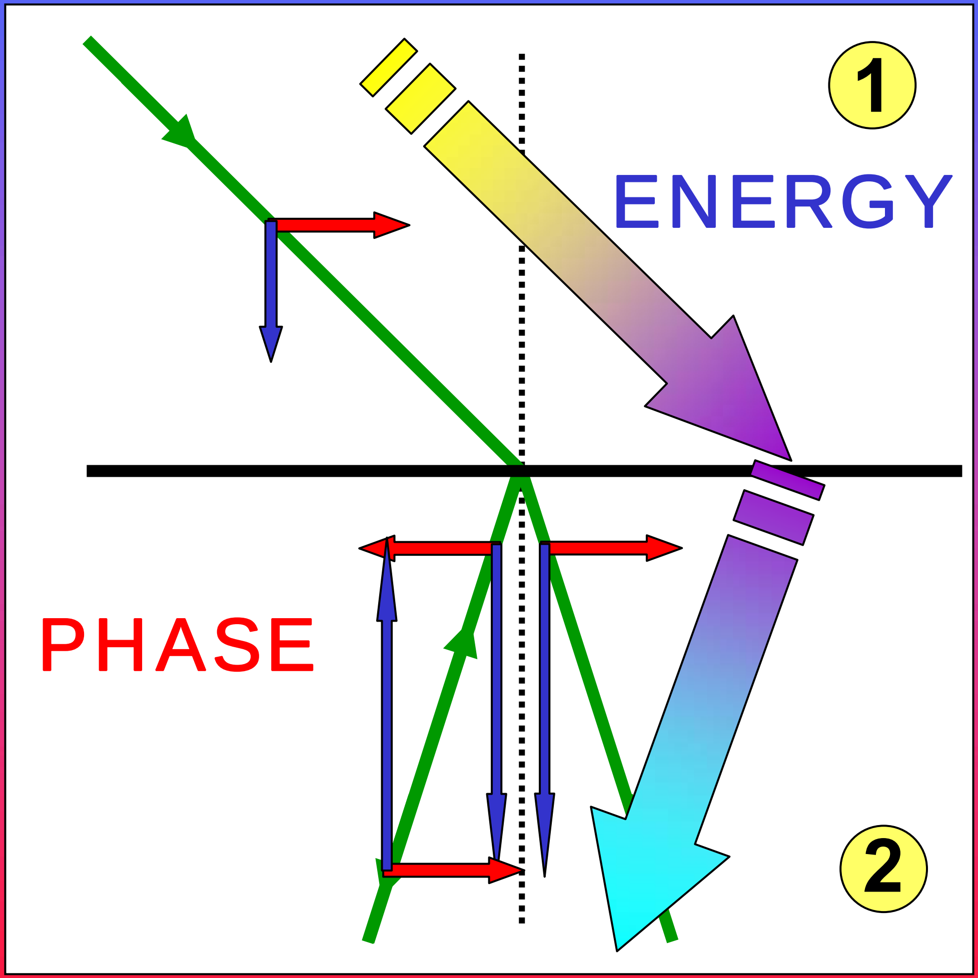
POSITIVE PHASE

NEGATIVE PHASE: BACKWARD WAVES

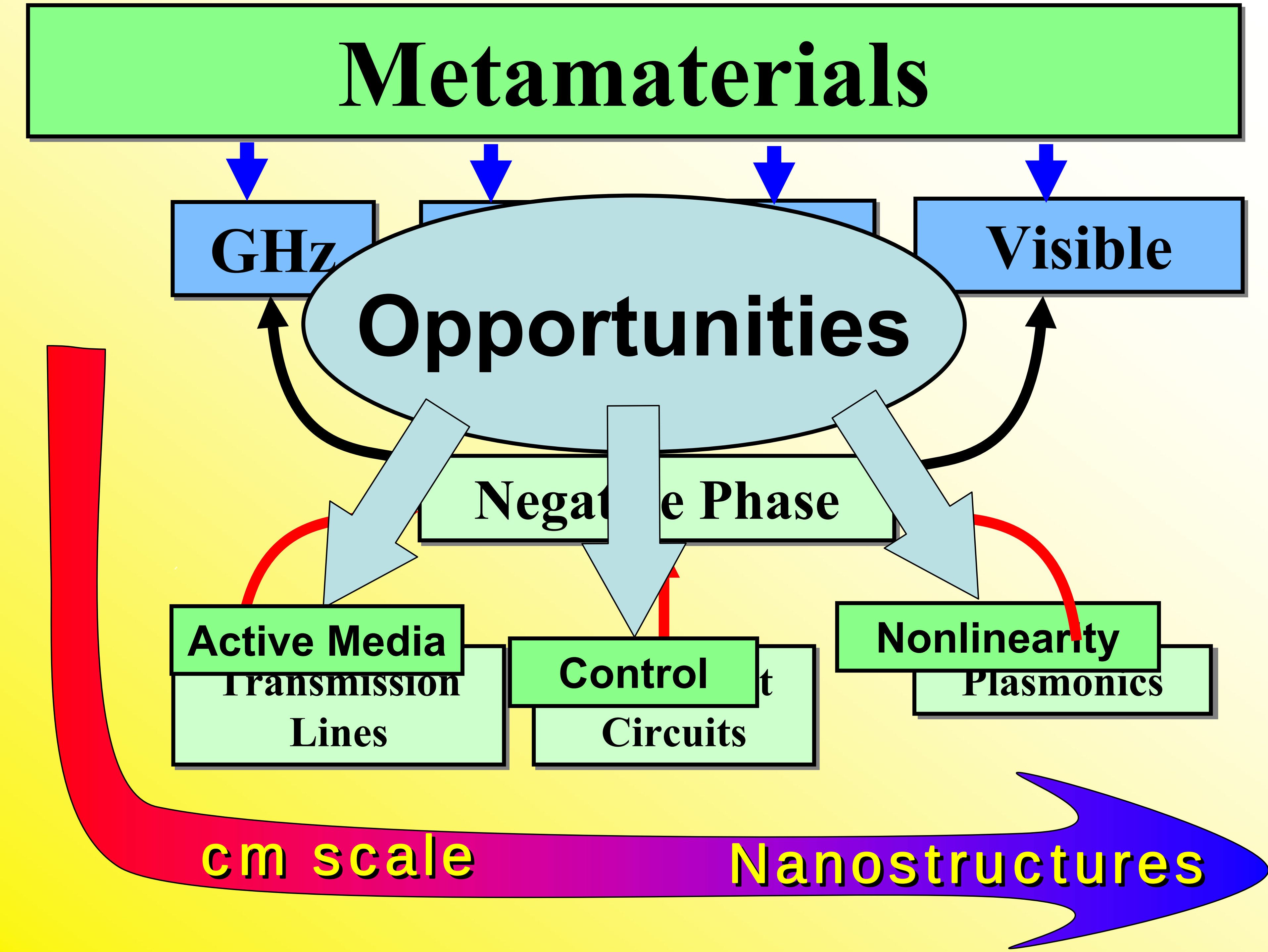
ABSORPTION

n = refractive index

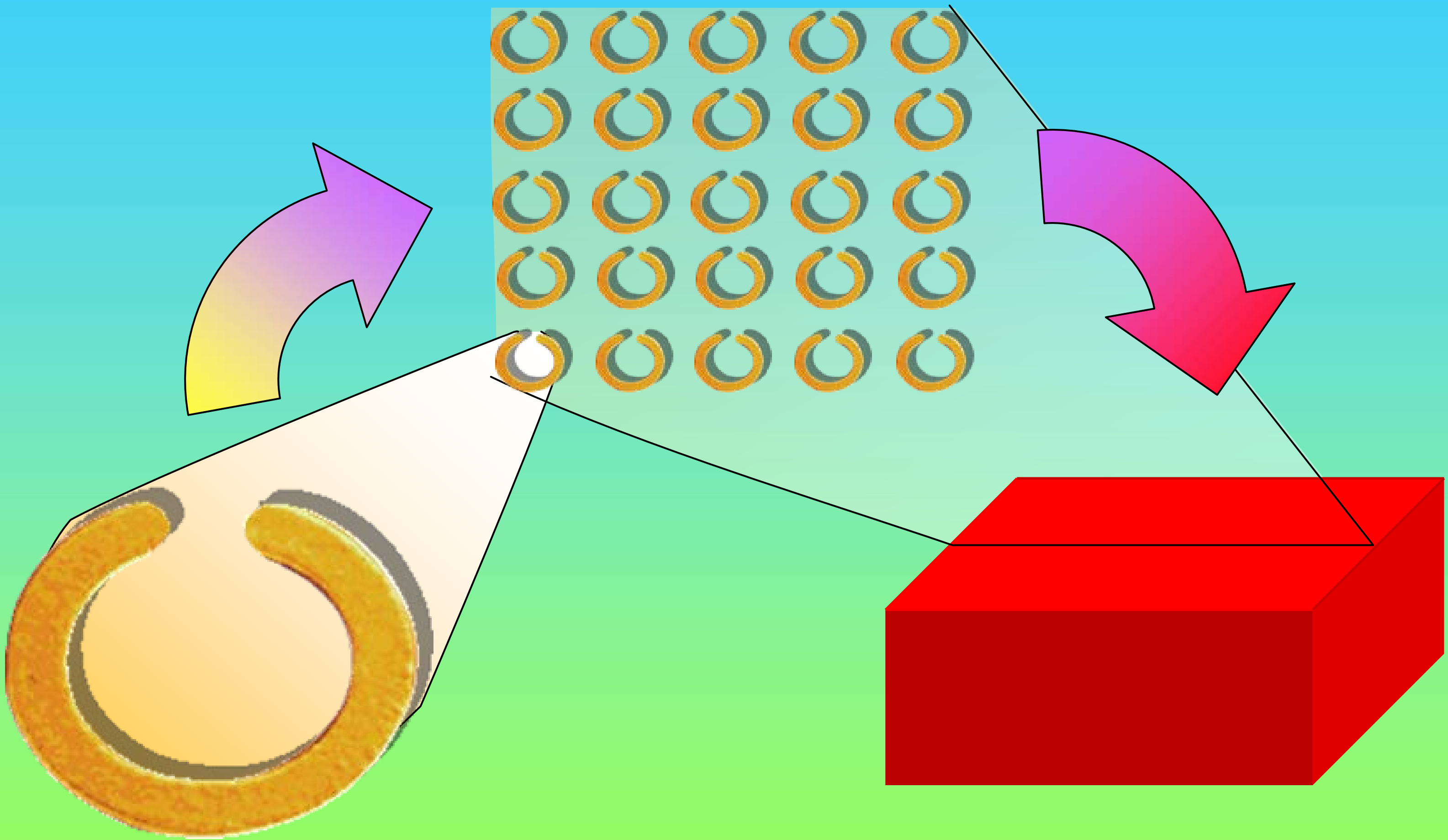
# Is This Refraction Possible?




**YES! AS A BACKWARD WAVE**


Metamaterials
GHz
Visible
Opportunities
Negat e Phase
Active Media
Transmission
Lines
Control
Circuits
Nonlinearity
Plasmonics
cm scale
Nanostructures

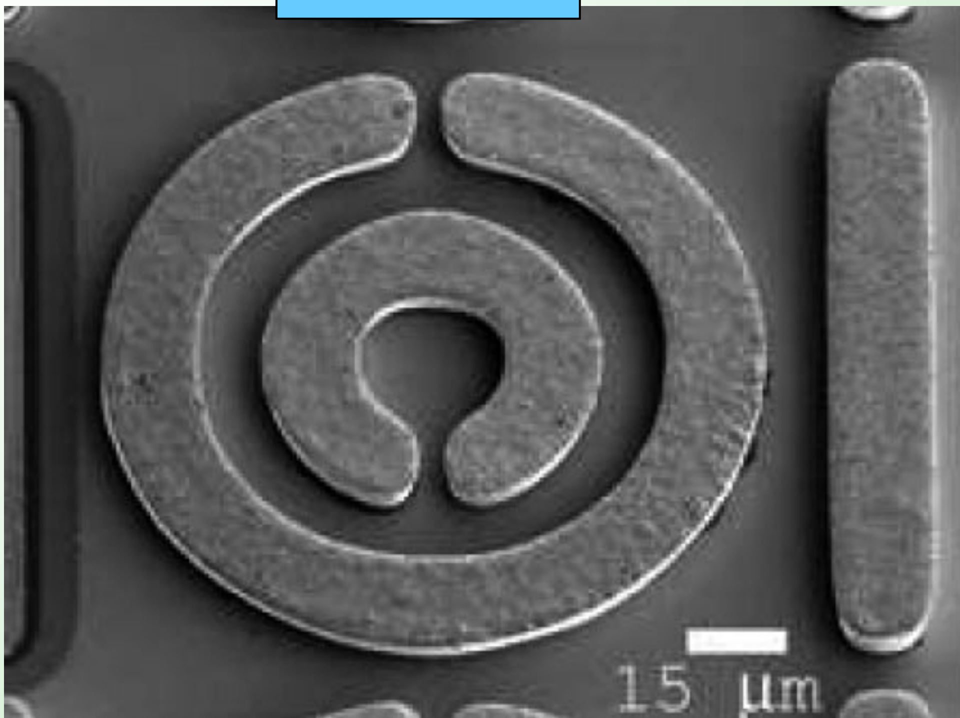
# Split-ring resonator



**Adding magnetic moments**

# Metamaterials

Low THz



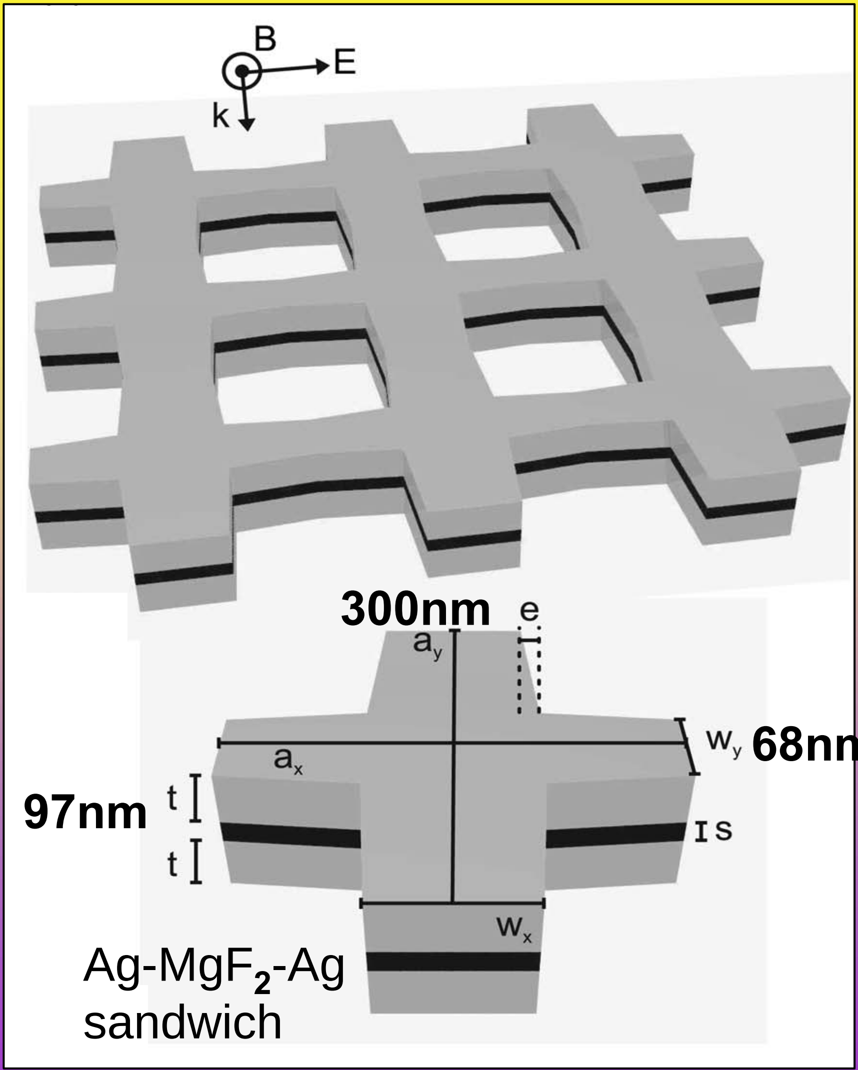

Moser PRL 94, 063901 (2005)

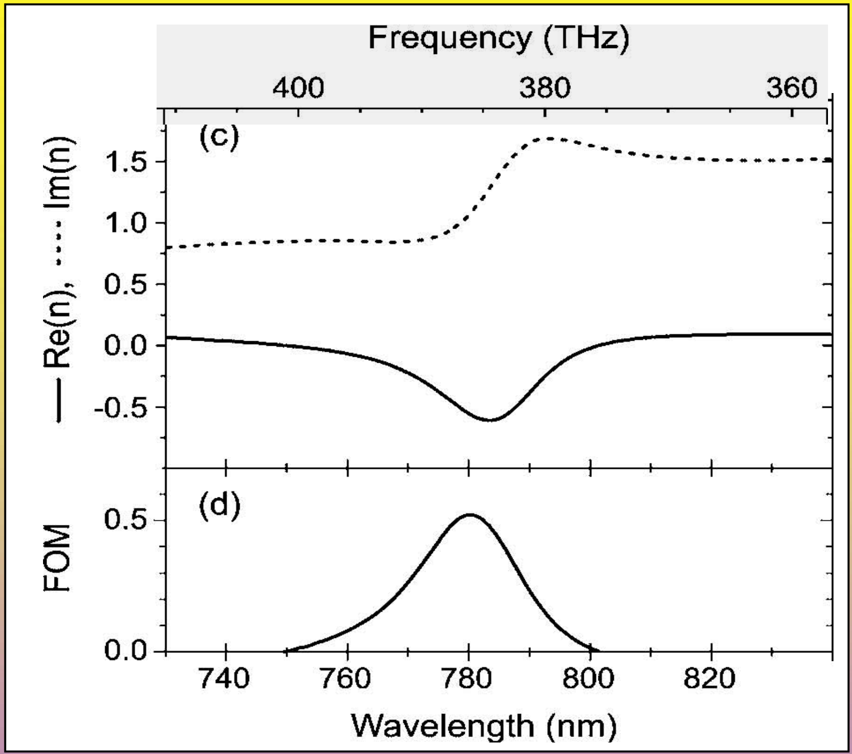
- Basically, what could they be?
- The big idea:
  Considerably enhance the magnetic properties

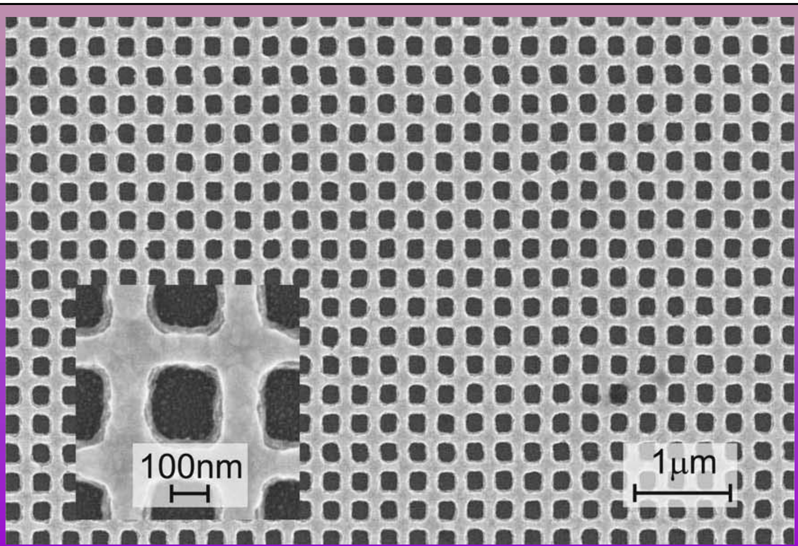
**Magnetic resonance**

# Modern Materials

# Operates at 780 nm



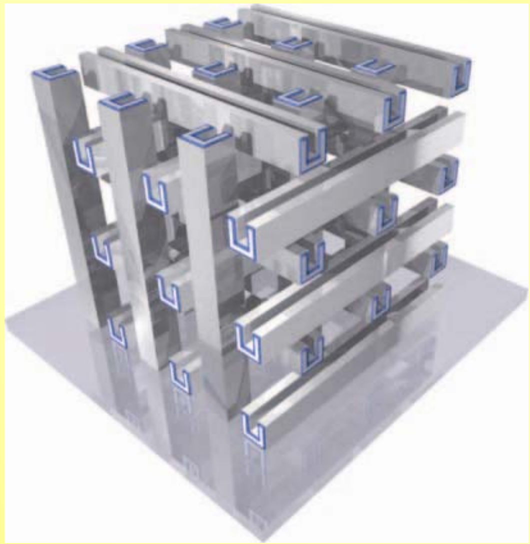



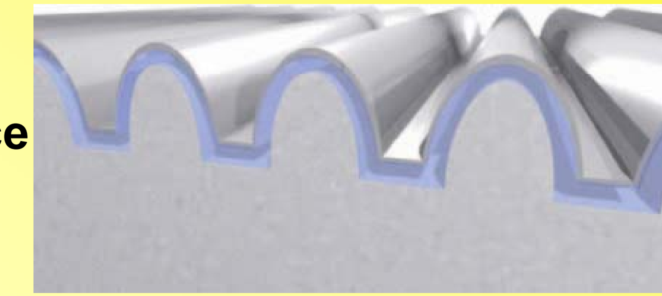

Dolling et al. Opt. Lett. **32** 53 (2007)

# Photonic Metamaterials by Direct Laser Writing and Silver Chemical Vapour Deposition

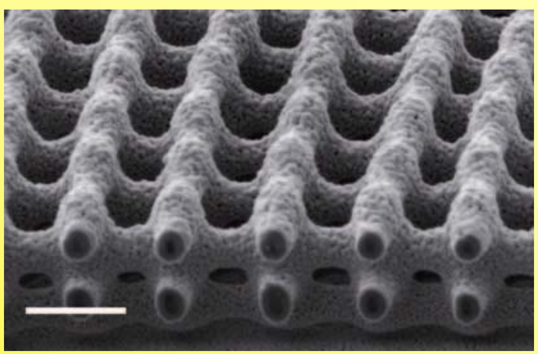
**Hypothetical 3D Split-ring Structure**



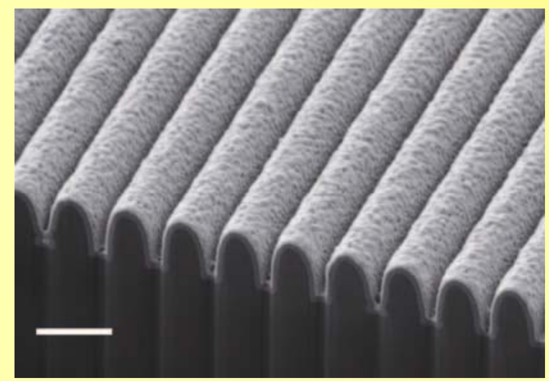
**Planar lattice Design**



**Fabricated 3D Structure composed of bars**

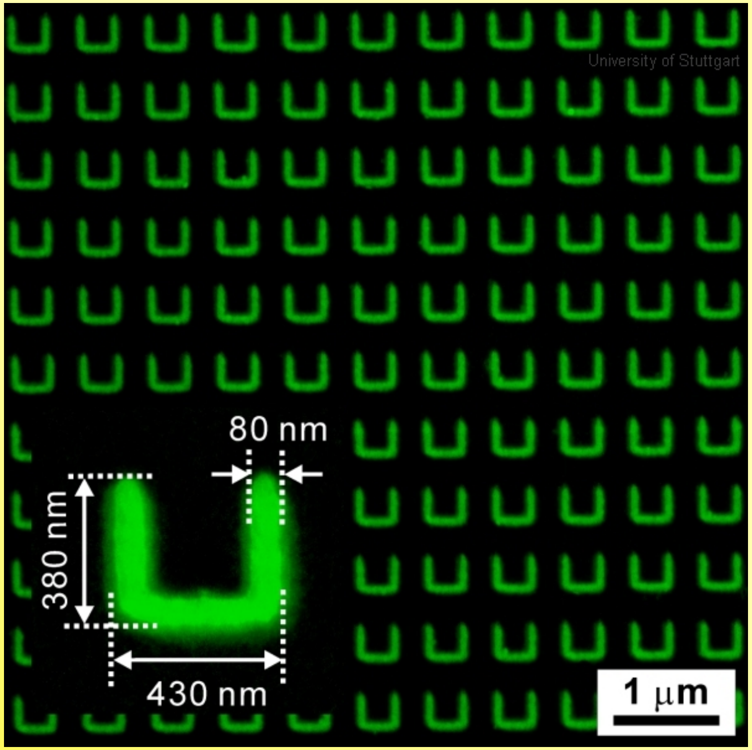


**Actual Fabrication**

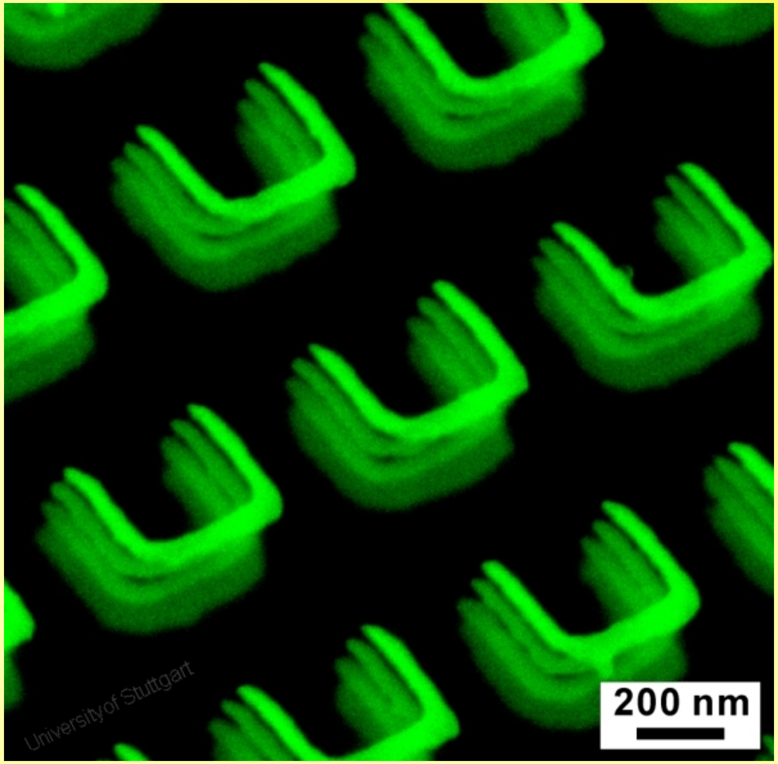


**Rill, Plet, Thiel, Staude, Freyman, Linden, Wegener, Nature Materials (Advance online publication) 1-4, (2008)**

# Field emission SEM images of Split-ring Resonators (SRR)




Four layer SRR structure

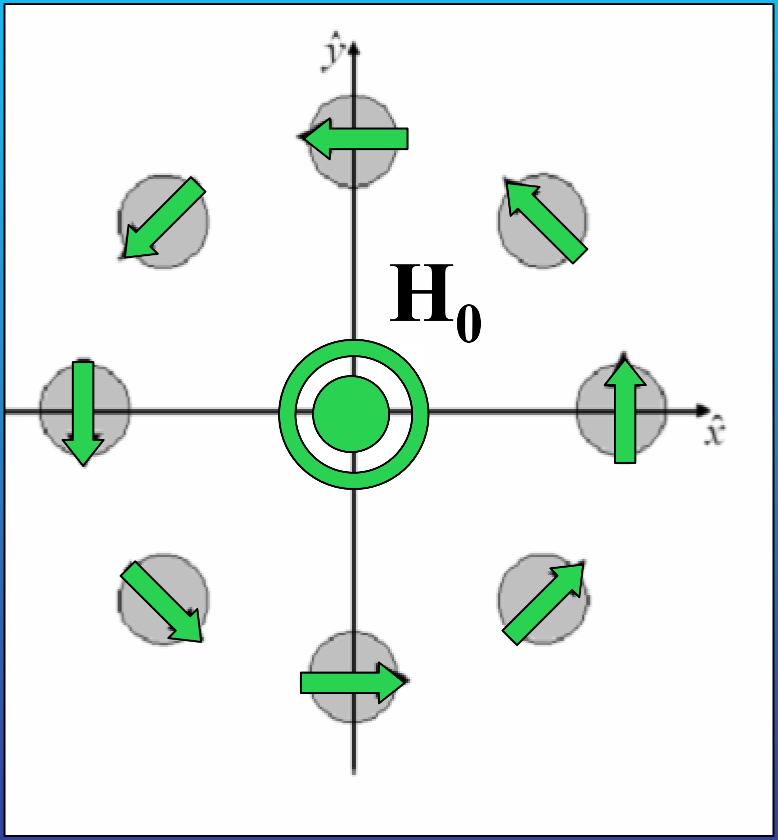



Enlarged Oblique view

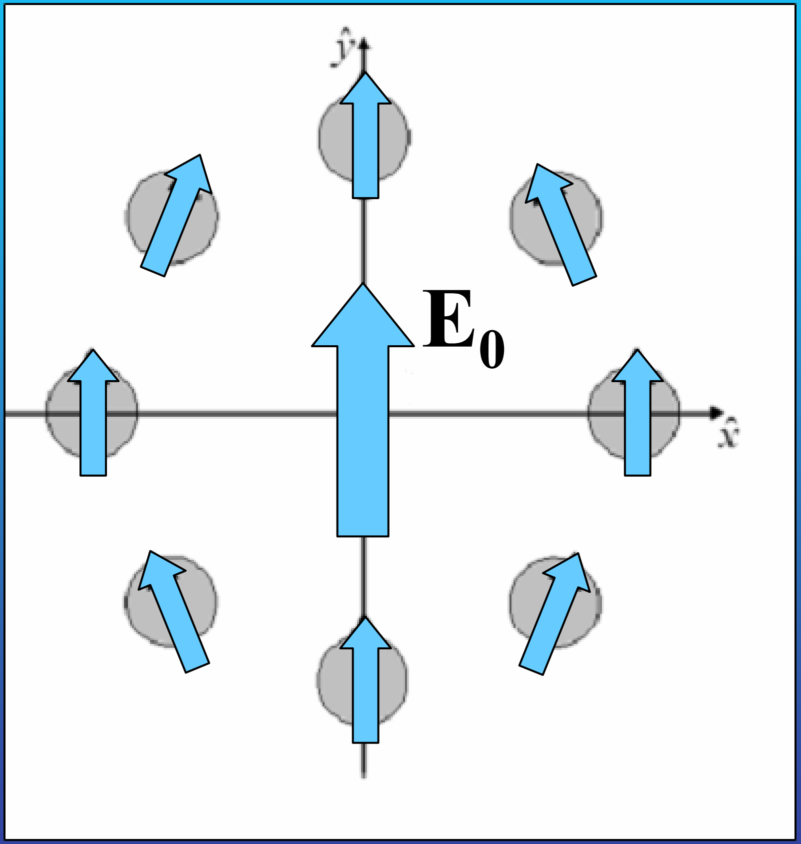
Liu, Guo, Fu, Kaiser, Schweizer, Giessen, Nature Materials, 7, 31-37 (2007)

# Nanospheres

**Magnetic resonance**

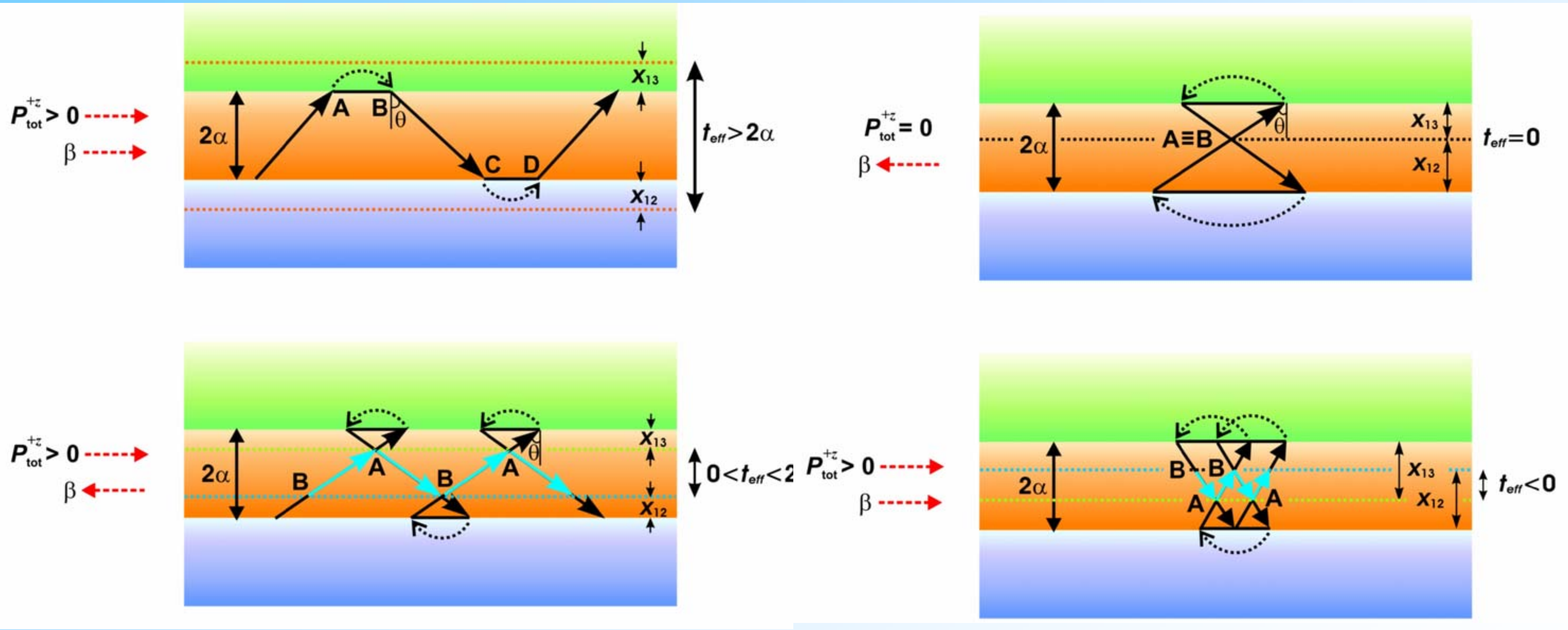



**Electric resonance**




Alu et. al, Opt. Exp. **14**, 1557 (2006)

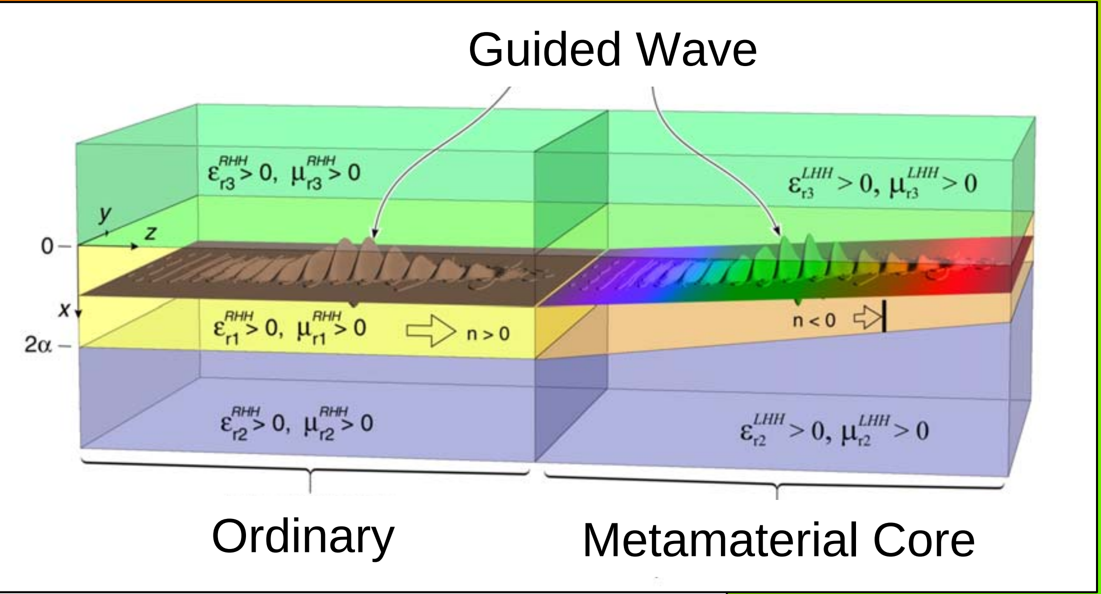
# Trapped Rainbows

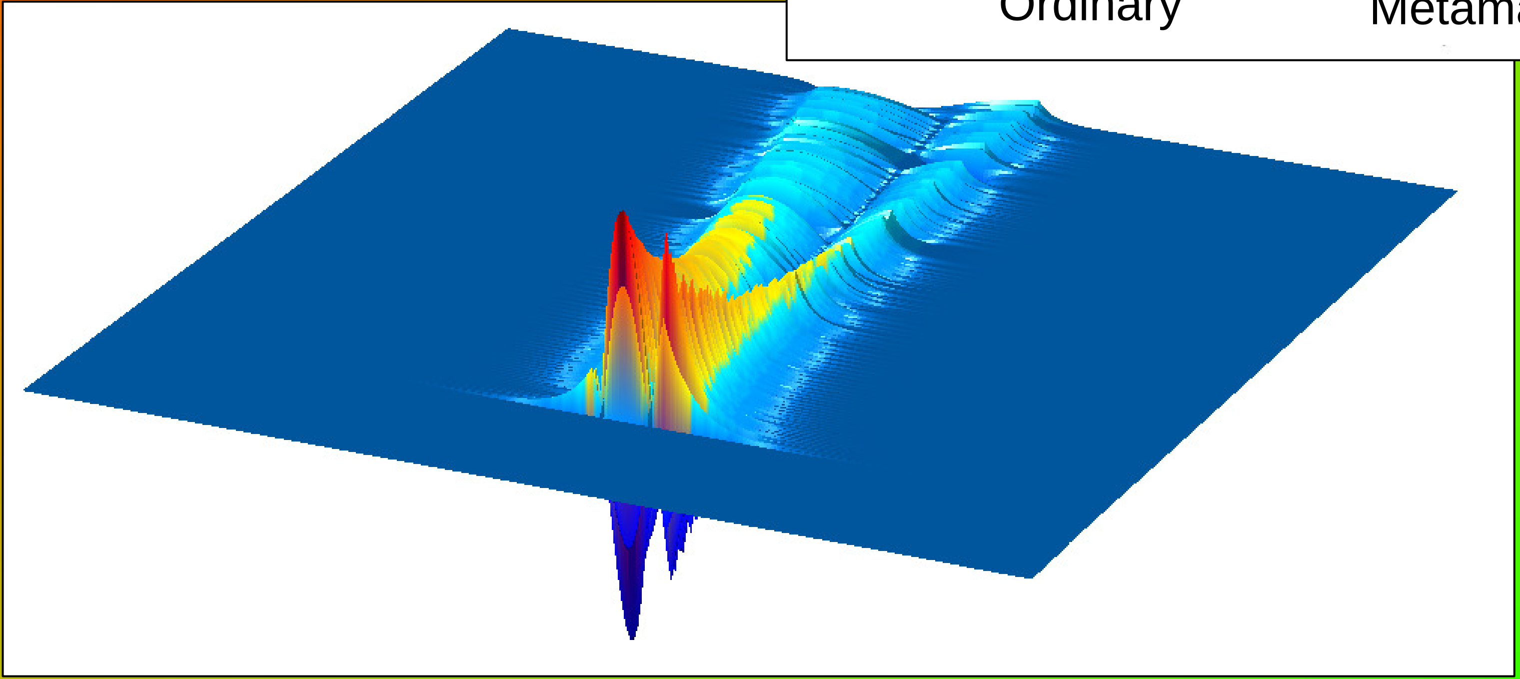



Tsakmakidis, Boardman, Hess, Nature (submitted July 2007)

# Trapped Rainbow

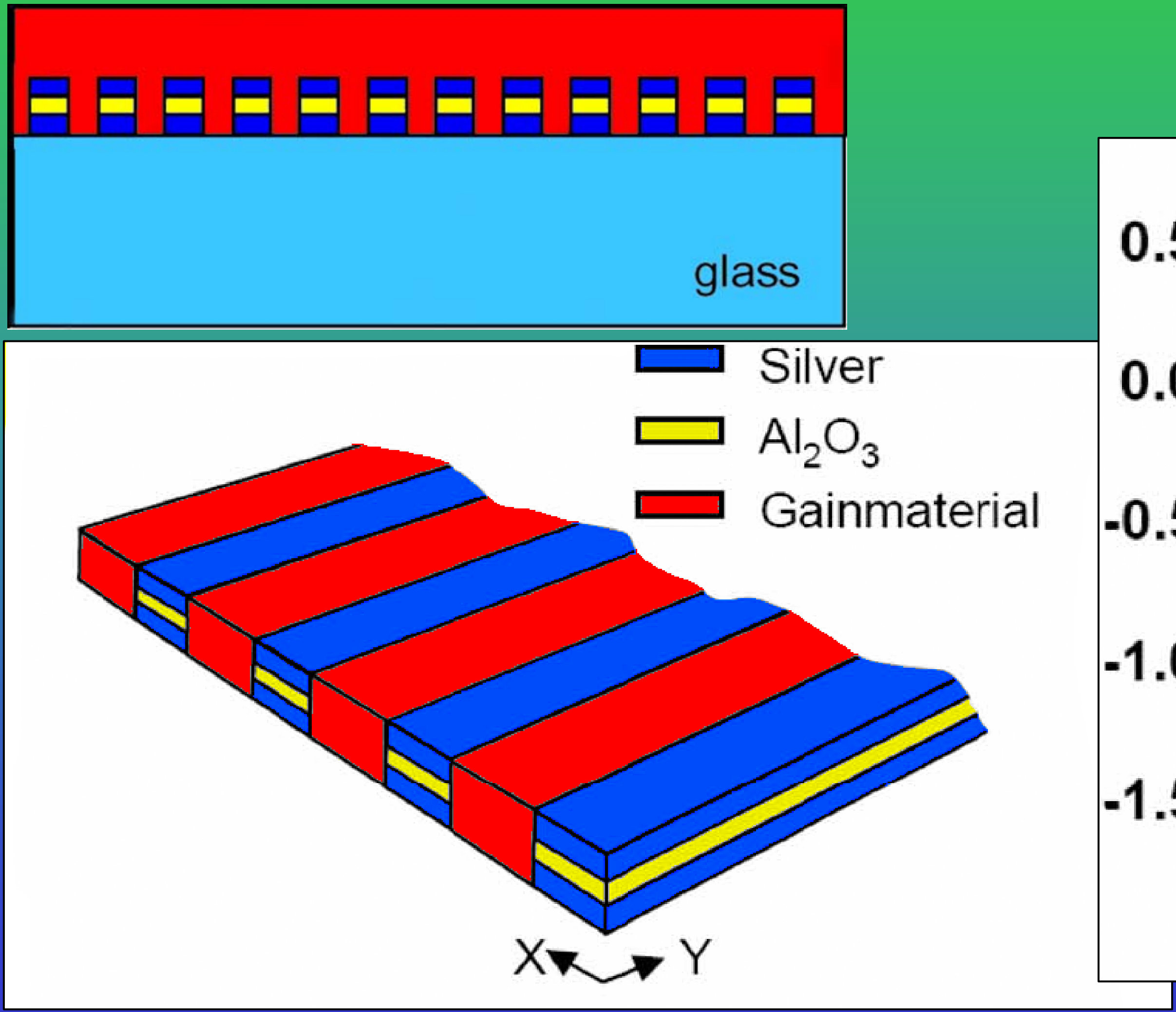
**Tapered Waveguide**

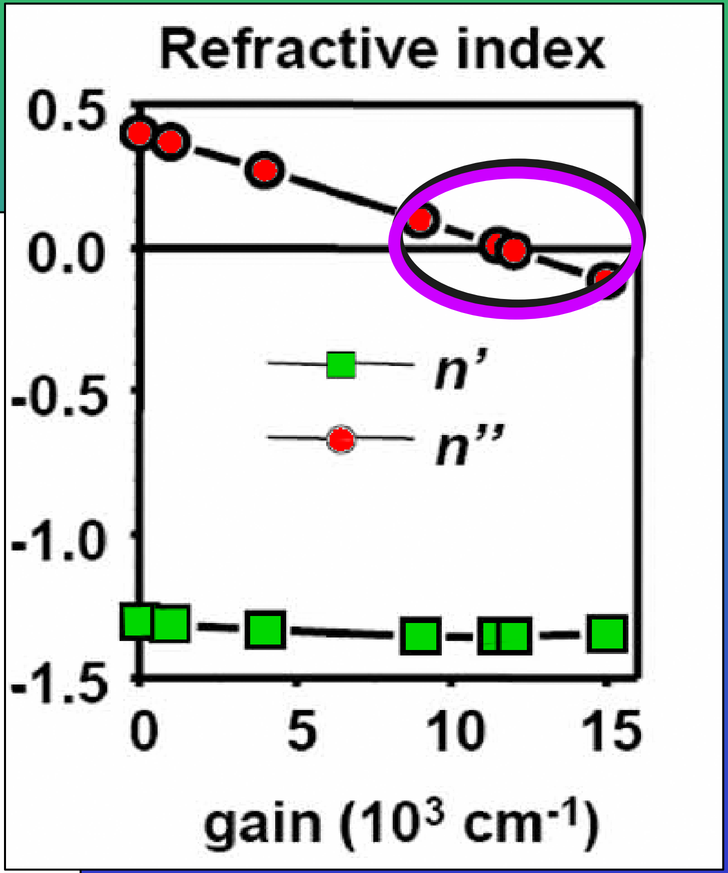


# Roads to gain

# GAIN WITH NANOSTRIPS




Klar et al. IEEE J. Sel. Top. Q. Elec., **12** (2006)

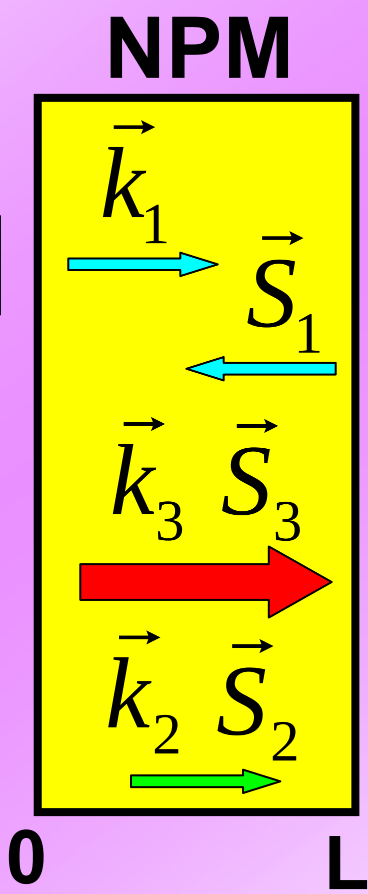
# Optical Parametric Amplification

**NPM = negative phase velocity medium ≡ LHM ("left-handed" medium)**

**Signal backward wave**

**Pump forward wave**

**Idler forward wave**



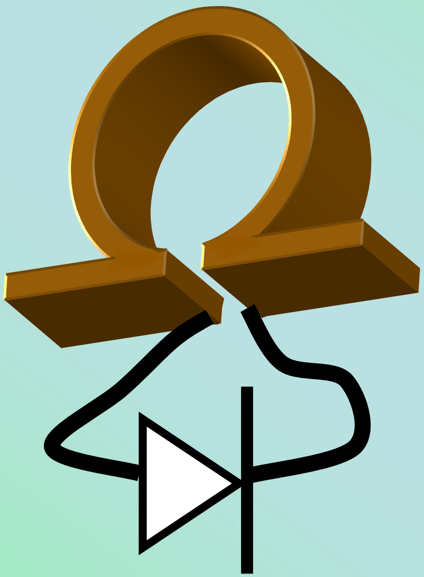

**$\Delta k = k_3 - k_2 - k_1$**

OPA causes energy to flow from the 3 to 1 through the idler wave $k_2$

A.K. Popov and V.M. Shalaev Optics Lett. **31**, 2169 (2006)

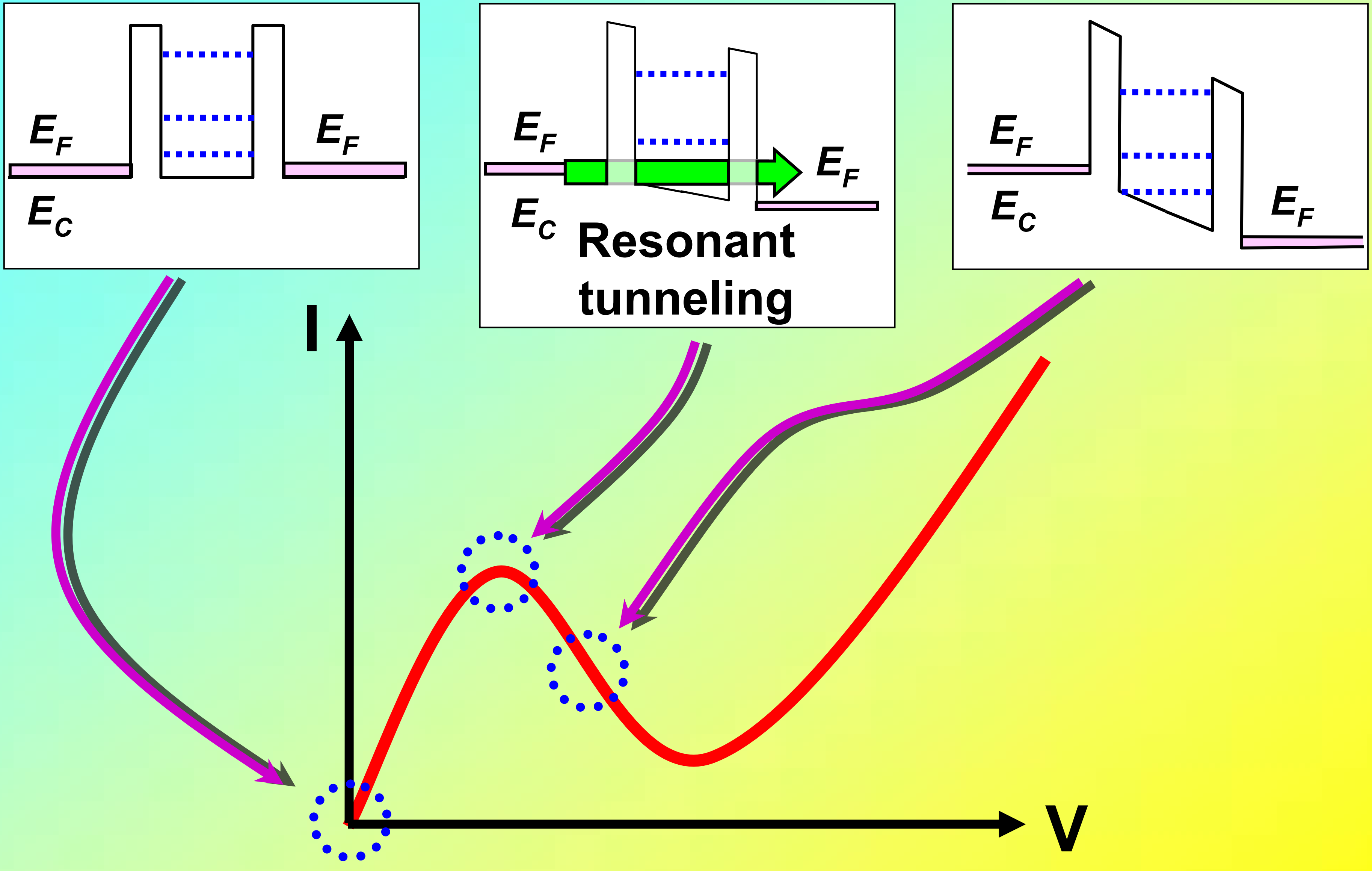
# How do we deal with losses?

- Add internal gain using active inclusions e.g. diodes

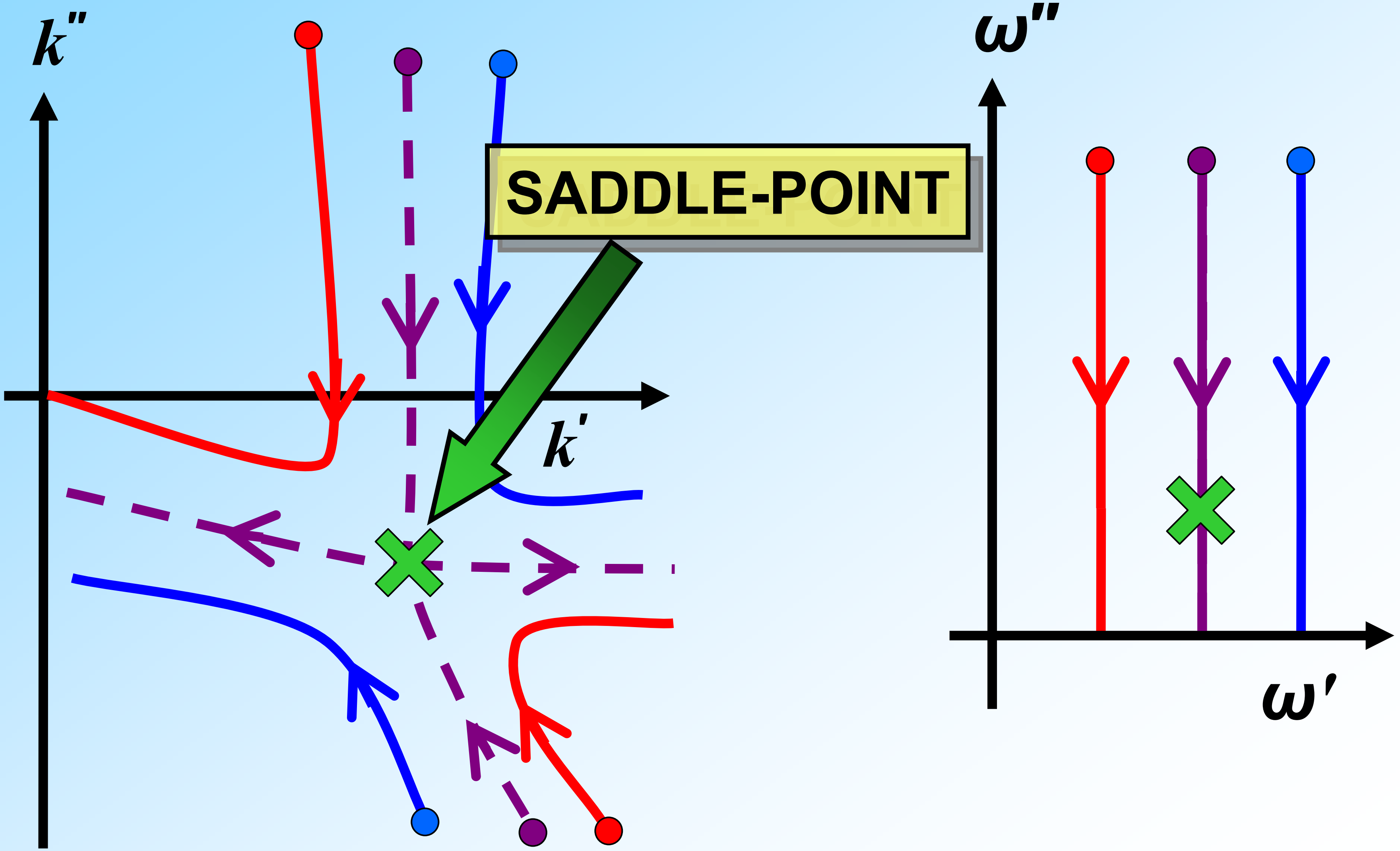


- Use optical pumping at higher frequencies

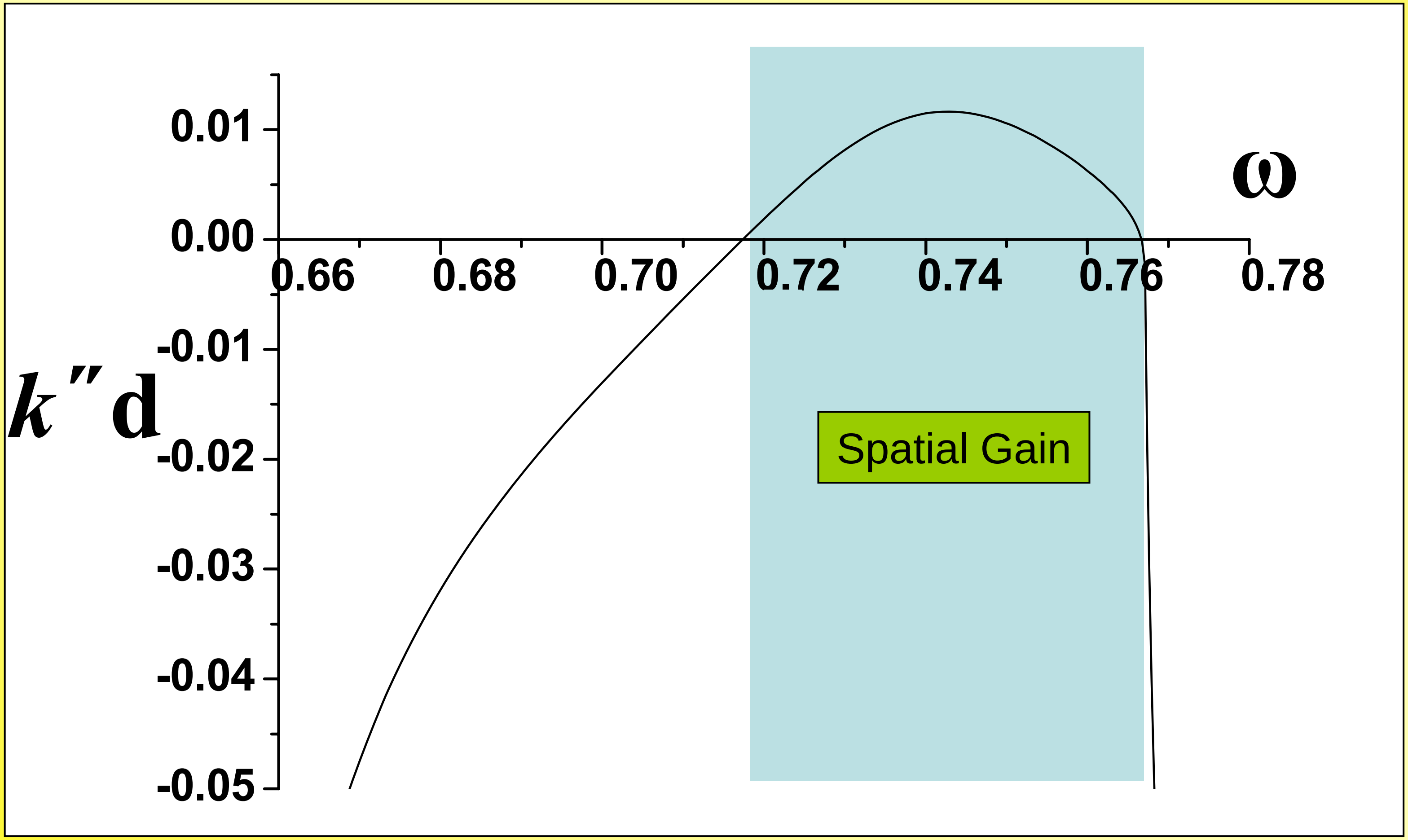
# Negative Resistance



# Mapping complex ω-plane onto complex k-plane

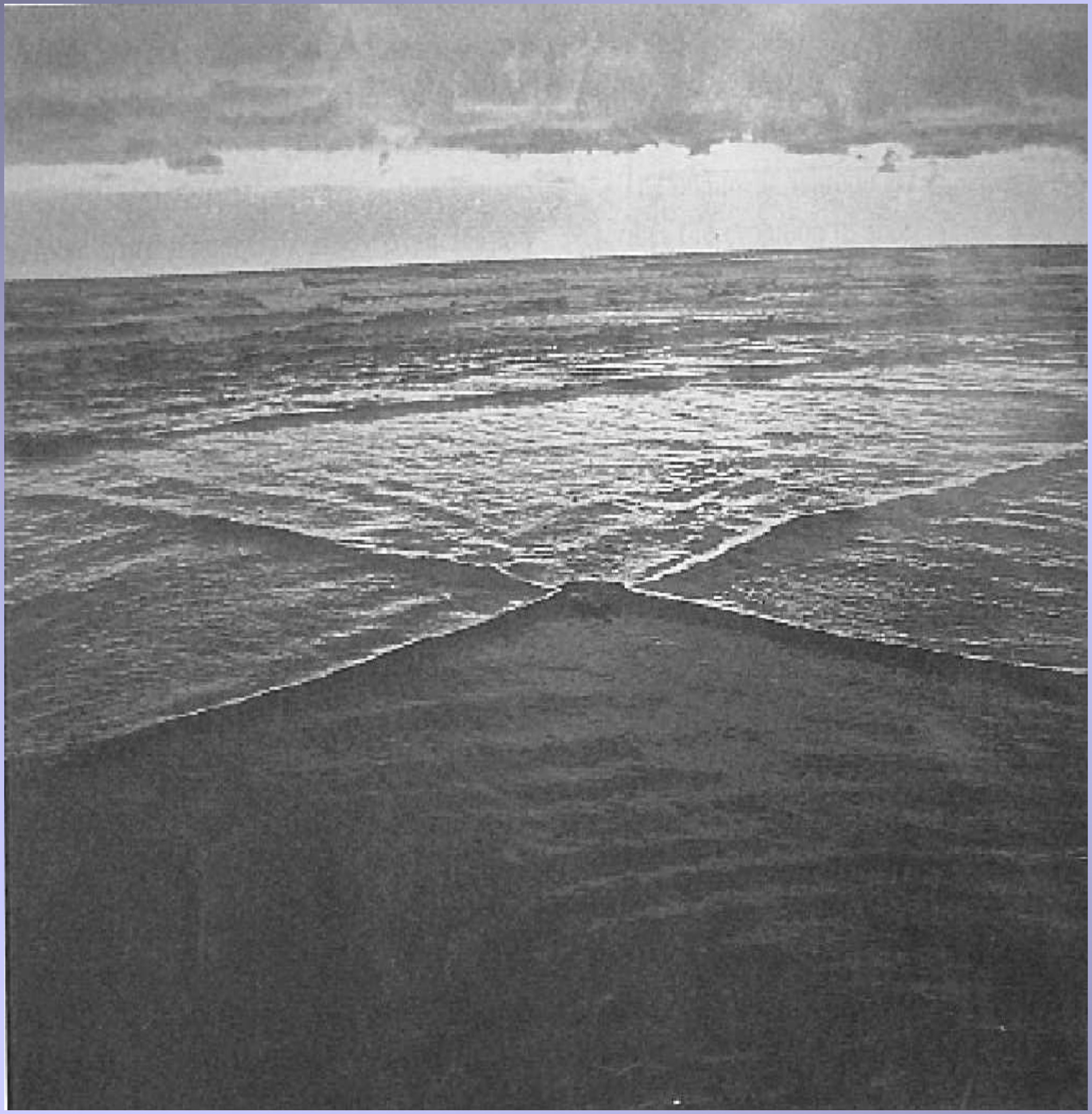


# Convective instability




Boardman. King, Rapoport, Metamaterials

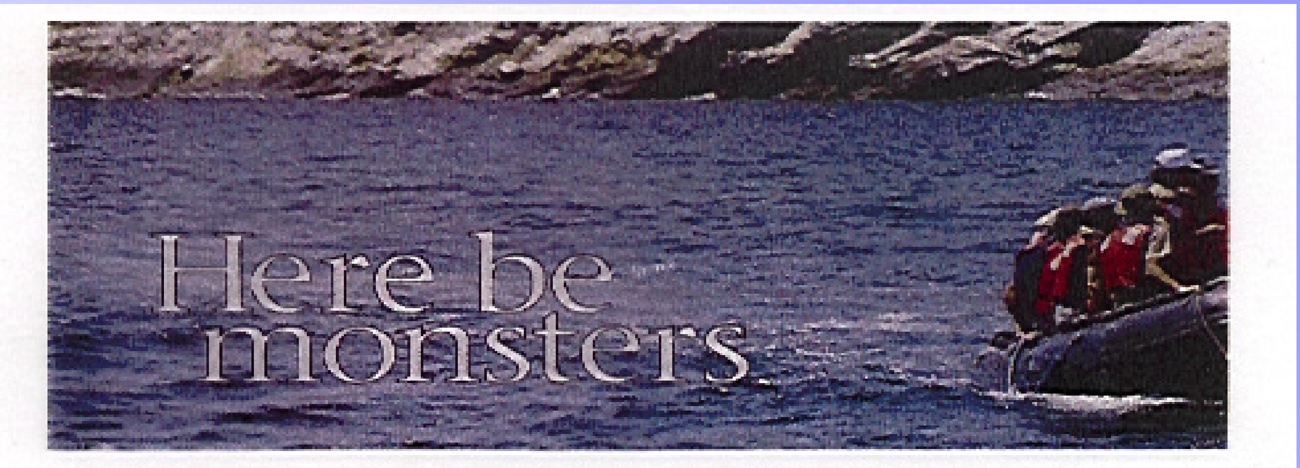
# Solitons



***CROSSING WAVES IN SHALLOW WATER***

***( Branksome Chine near Bournemouth)***

# Gravity waves on deep water




***Waves are solutions of***

*NONLINEAR SCHRODINGER EQUATION*

$$\mathbf{i}\frac{\partial \mathbf{U}}{\partial \mathbf{t}} = -\frac{\partial^2 \mathbf{U}}{\partial \mathbf{z}^2} - 2|\mathbf{U}|^2 \mathbf{U}$$

$$\bar{E} = U\exp(ikz - i\omega t)$$

***Looks like***

***quantum cousin***

$$\mathbf{i}\frac{\partial \psi}{\partial \mathbf{t}} = -\frac{\partial^2 \psi}{\partial \mathbf{z}^2} - \mathbf{V}(\mathbf{z})\psi$$

# *New Dawn*

Solitons for computing, nanophotonics, biology ...

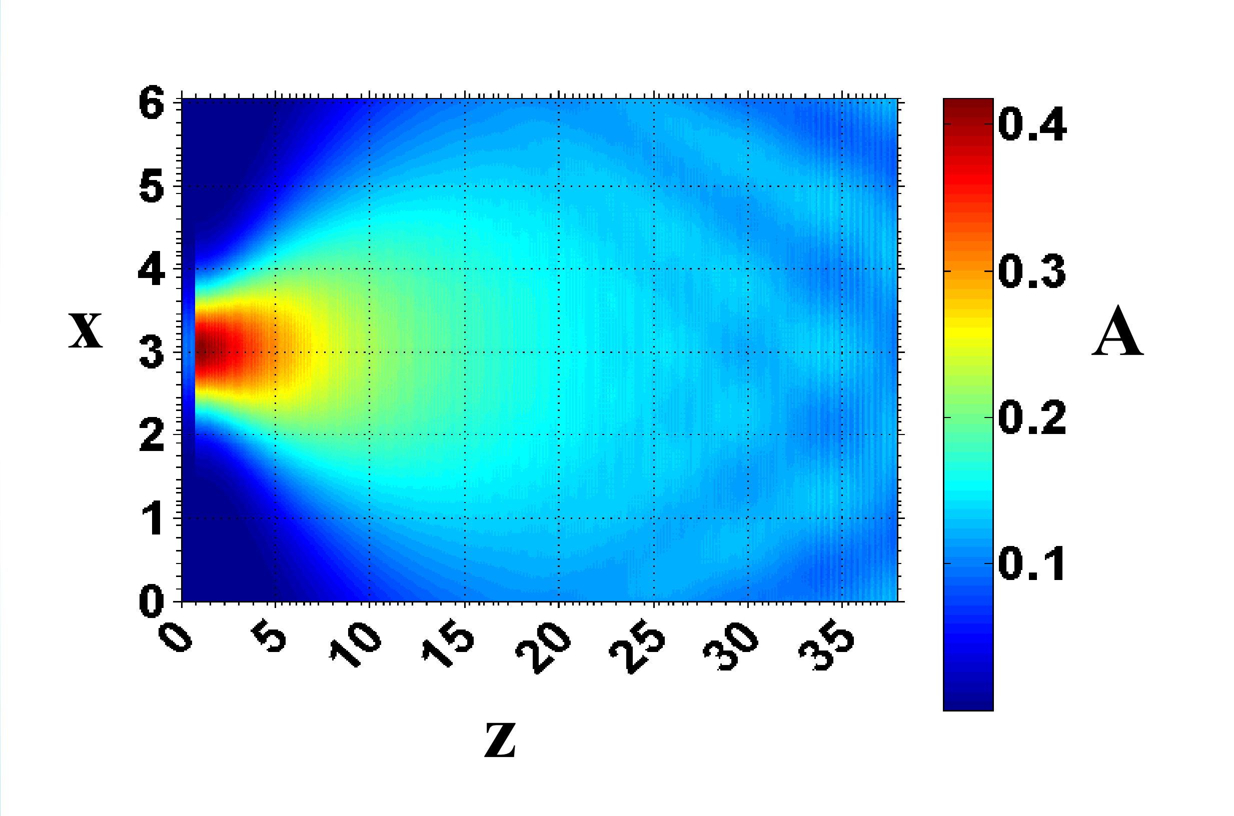
1965-67 Zabusky and Kruskal
Solitons and Inverse Scattering

1953 & 1962 Solution of sine-Gordon
Equation: Skyrmions

1895 Korteweg- de Vries
(KdV Solitons)

1834: John Scott Russell
First Observation: Solitary wave

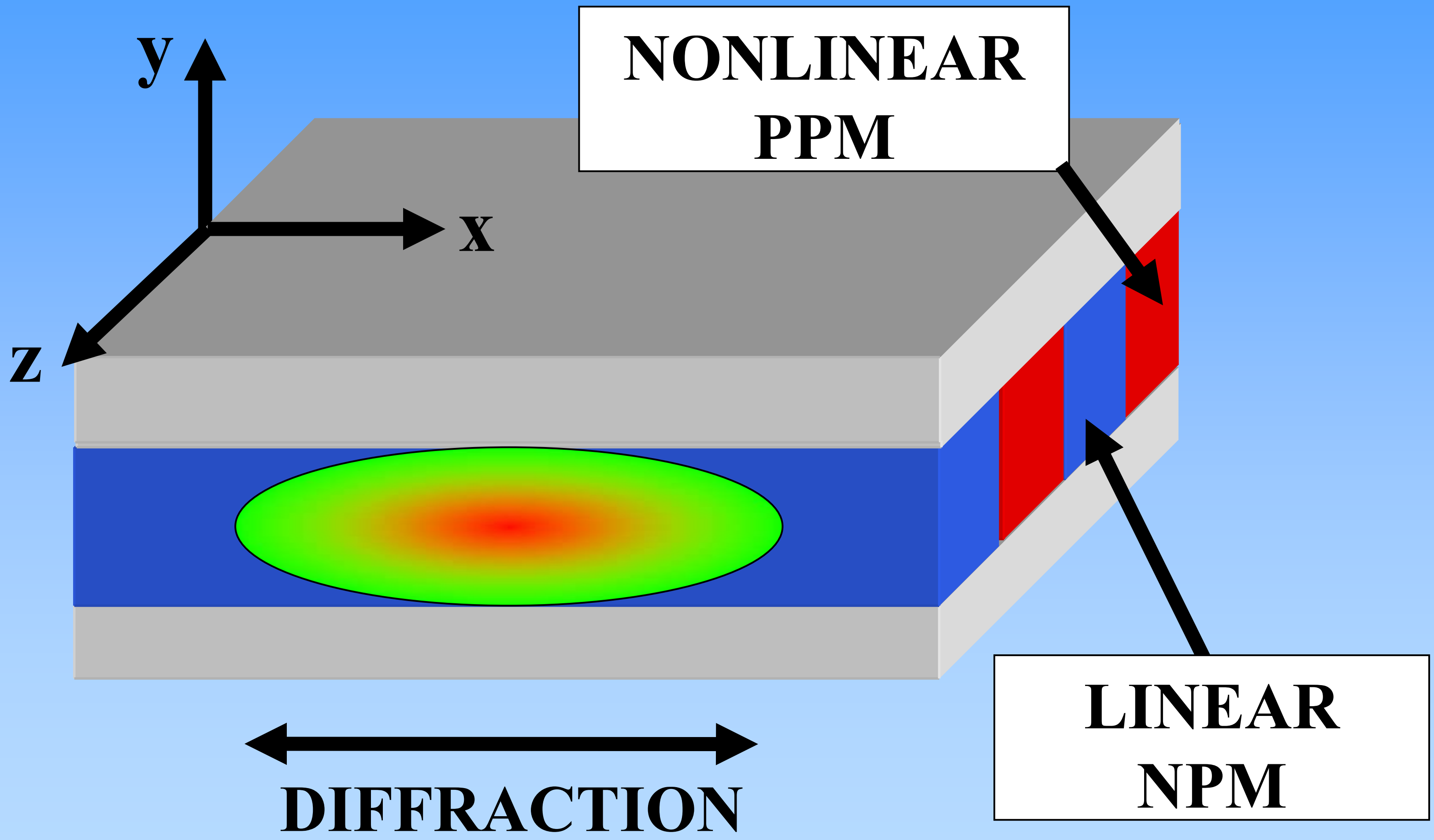
# Beam Diffraction




$$2ik \frac{\partial A}{\partial z} = -\frac{\partial^2 A}{\partial x^2}$$

# DIFFRACTION MANAGEMENT

# New Spatial Solitons



# Nonlinear Diffraction

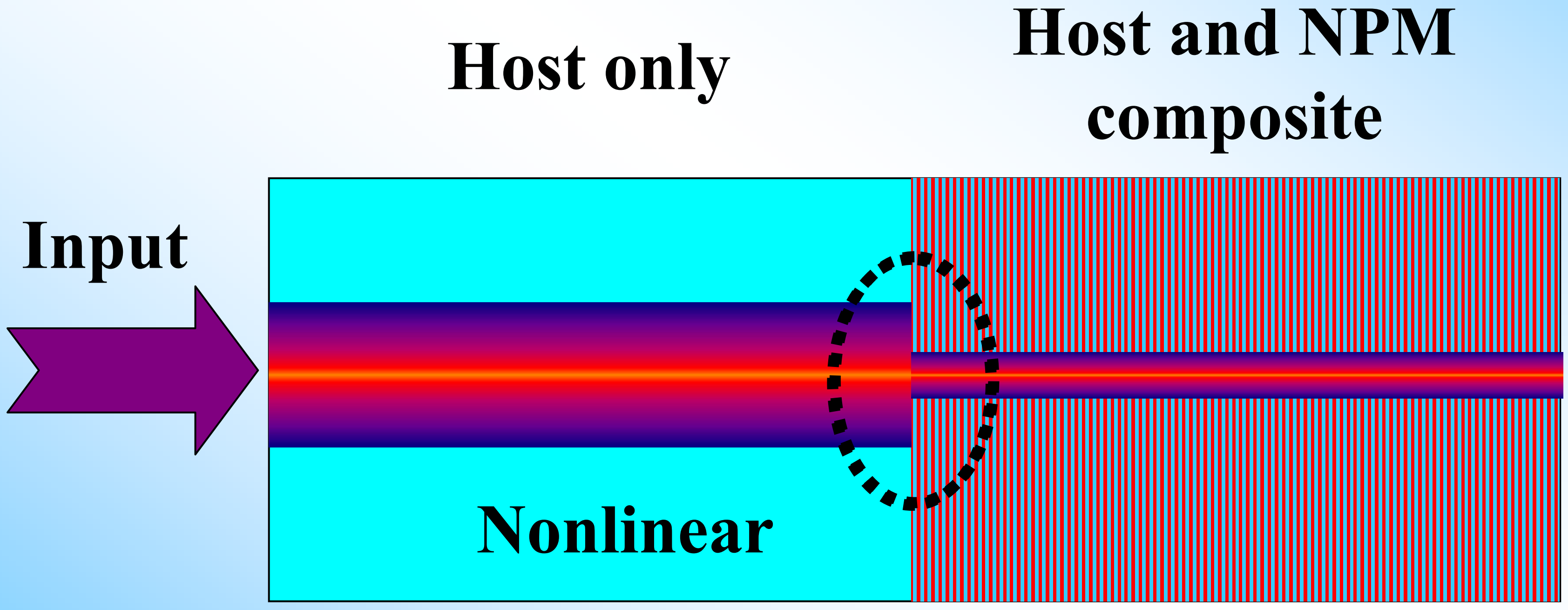
- Usual step is to set $\nabla.\mathbf{D} = 0$
- Here we have

$$\nabla \cdot \mathbf{D} = \varepsilon_0 \varepsilon_L \nabla \cdot \mathbf{E} + \nabla \cdot \mathbf{P}_{\mathrm{NL}} = 0$$

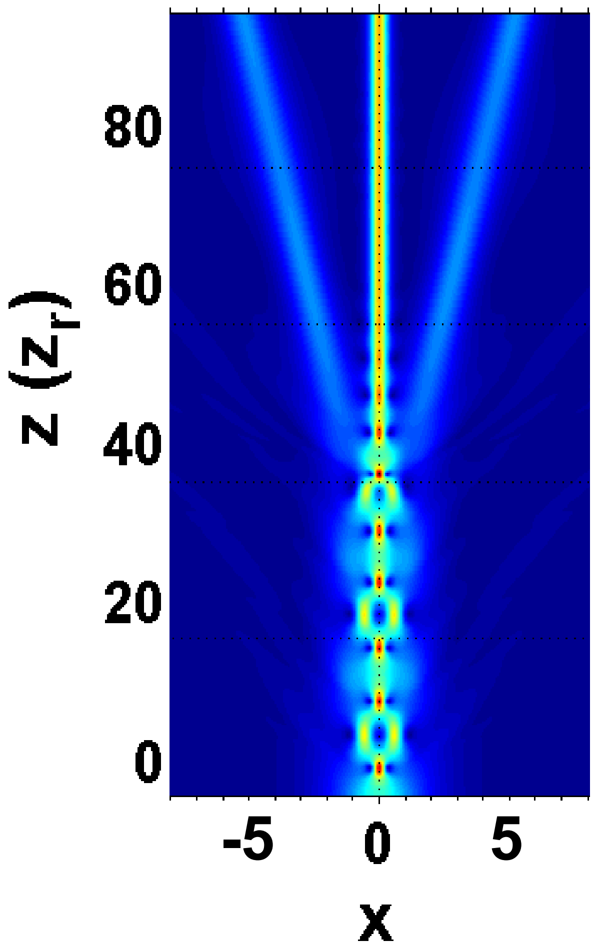
$$\frac{\varepsilon_{NL}^{(3)}}{\varepsilon} \frac{\partial^2}{\partial x^2}\left(\left|E_x\right|^2 E_x\right) \text{ added to NLS}$$

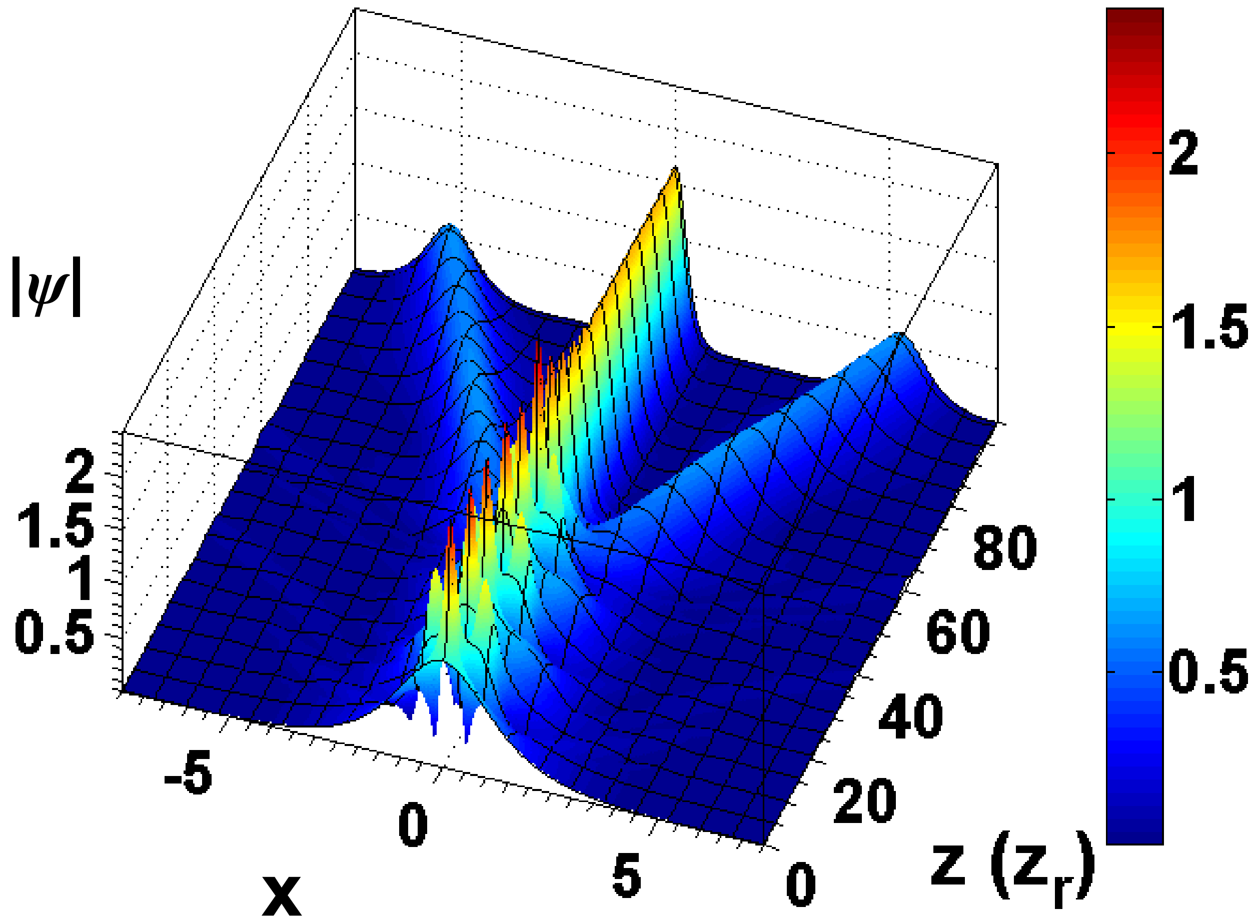
Boardman et al. Opt. Quant. Elec. **32** 49 (2000)

# Soliton Entering Composite



# Compensation with nonlinear diffraction

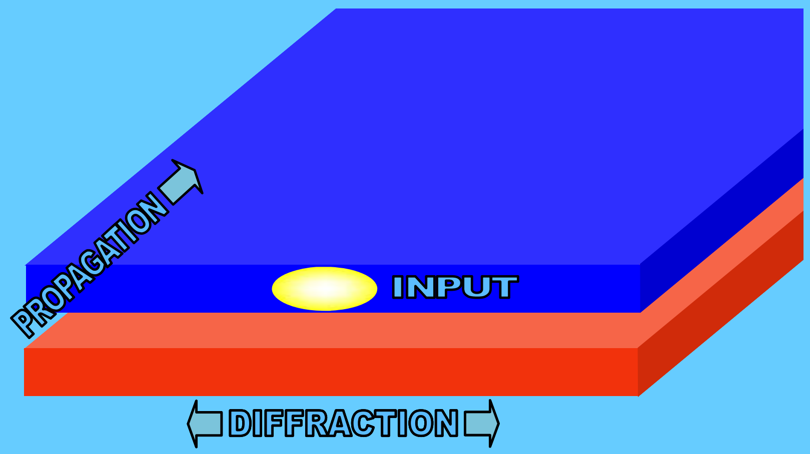


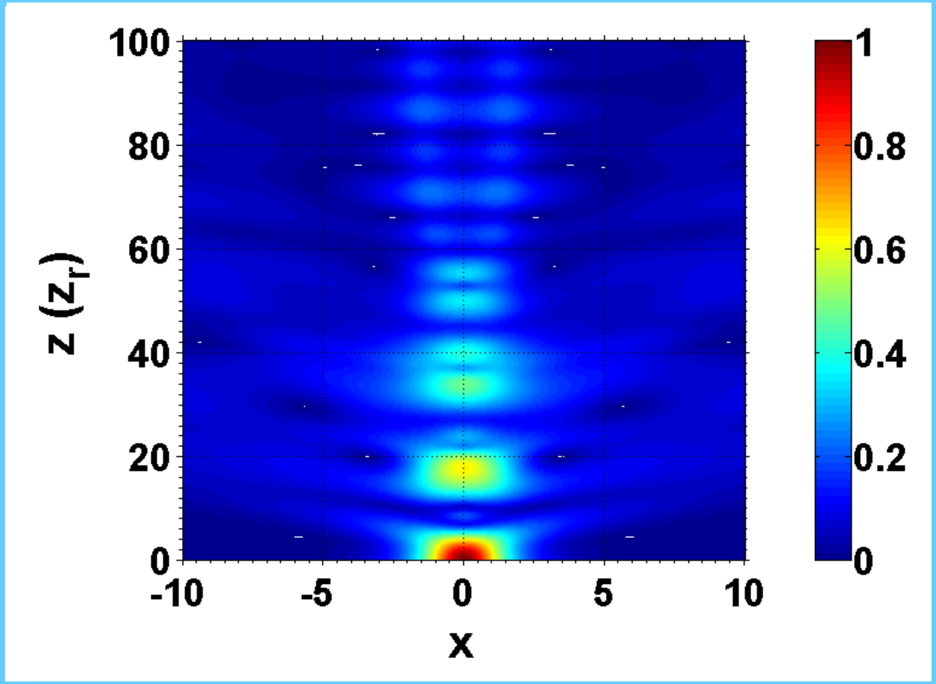




$$\psi\left(x,0\right) = \mathrm{sech}\left\{x\right\}$$

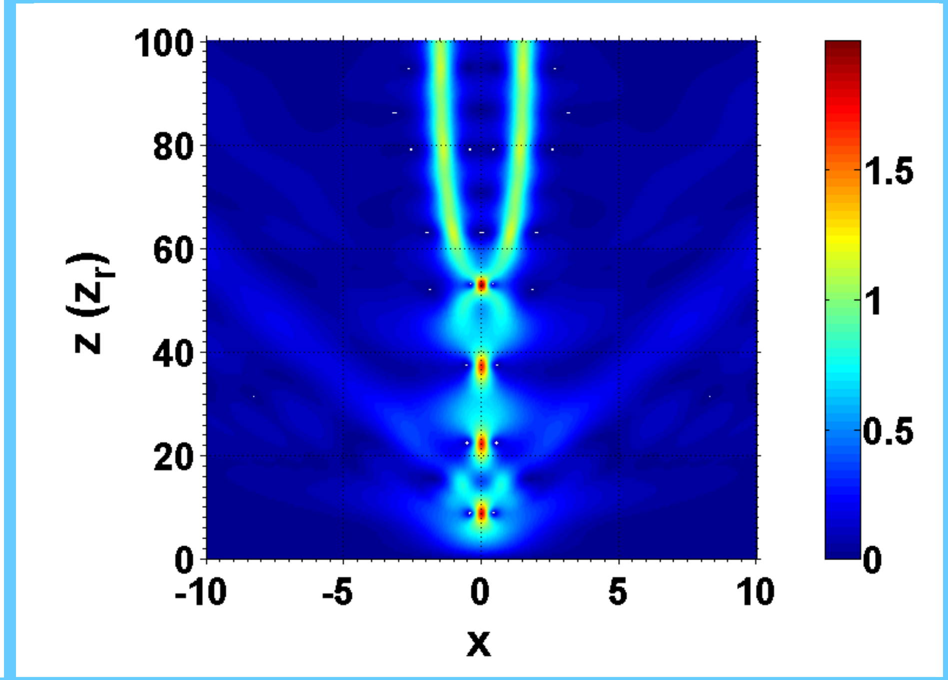
**D = 10%**

# How Does Diffraction Management Affect Coupling?



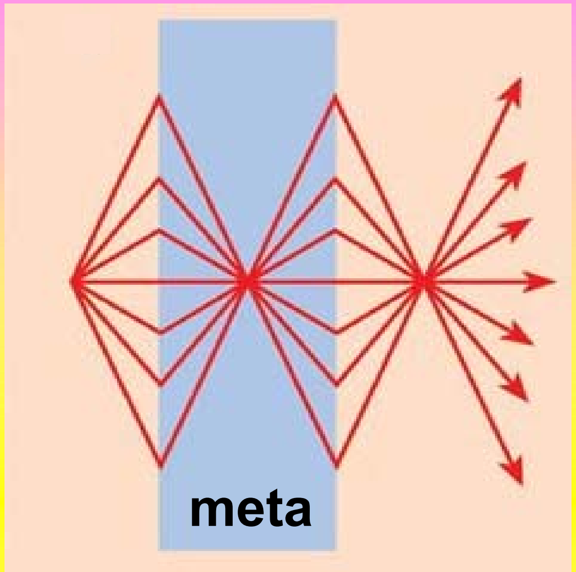

Input



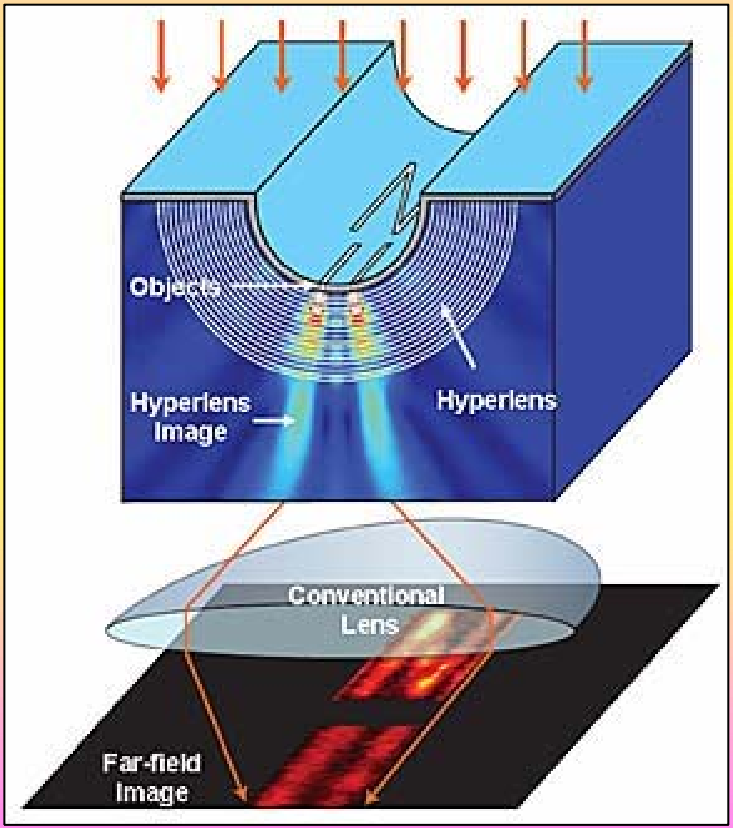
# More Possibilities

# Beating the Diffraction limit

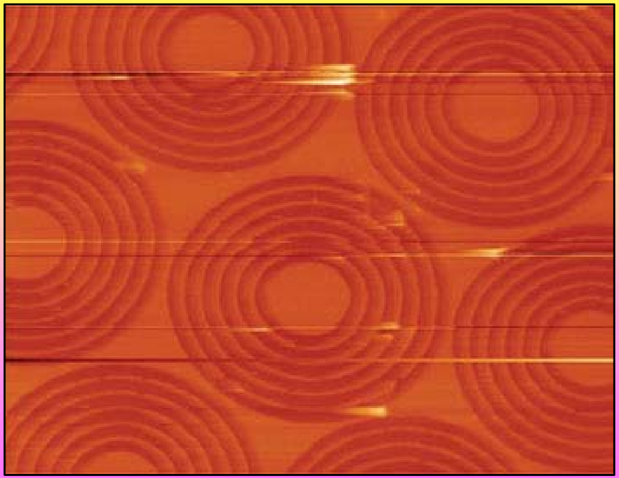
**Pendrys Perfect lens**




Zhang et al. Opt. Exp. 15, 15886, (2007)



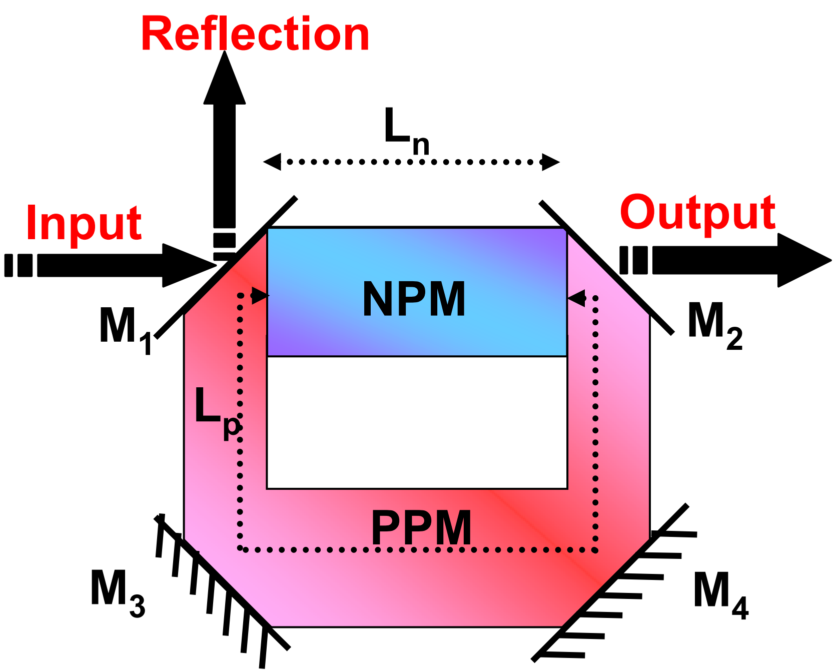

**Superlens and Hyperlens**

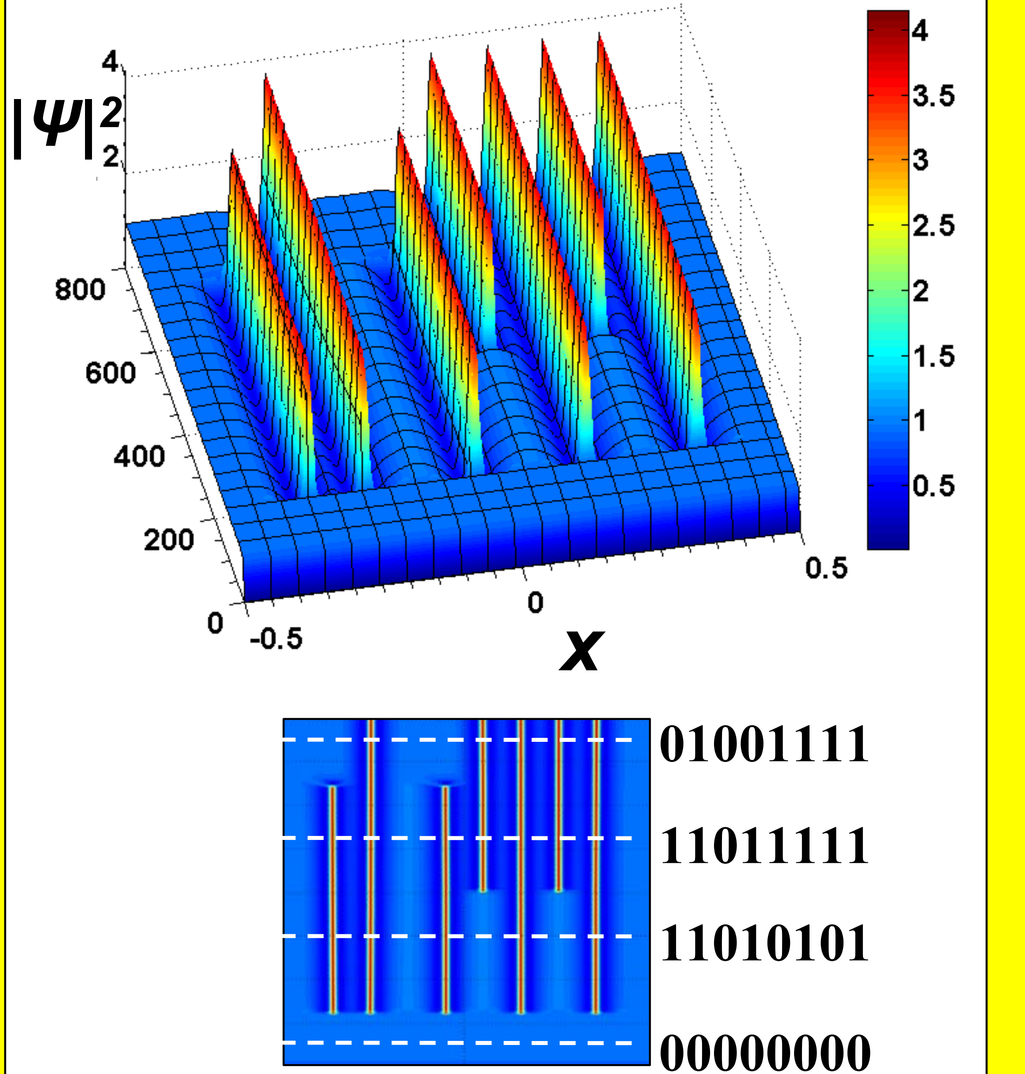


Smolynaninov, PRB 76, 205424, (2007)

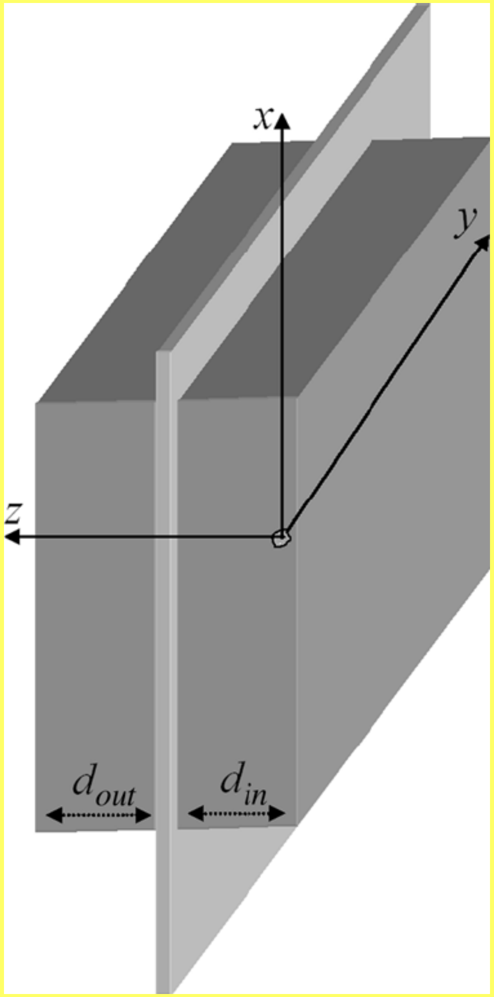
# Optical Storage

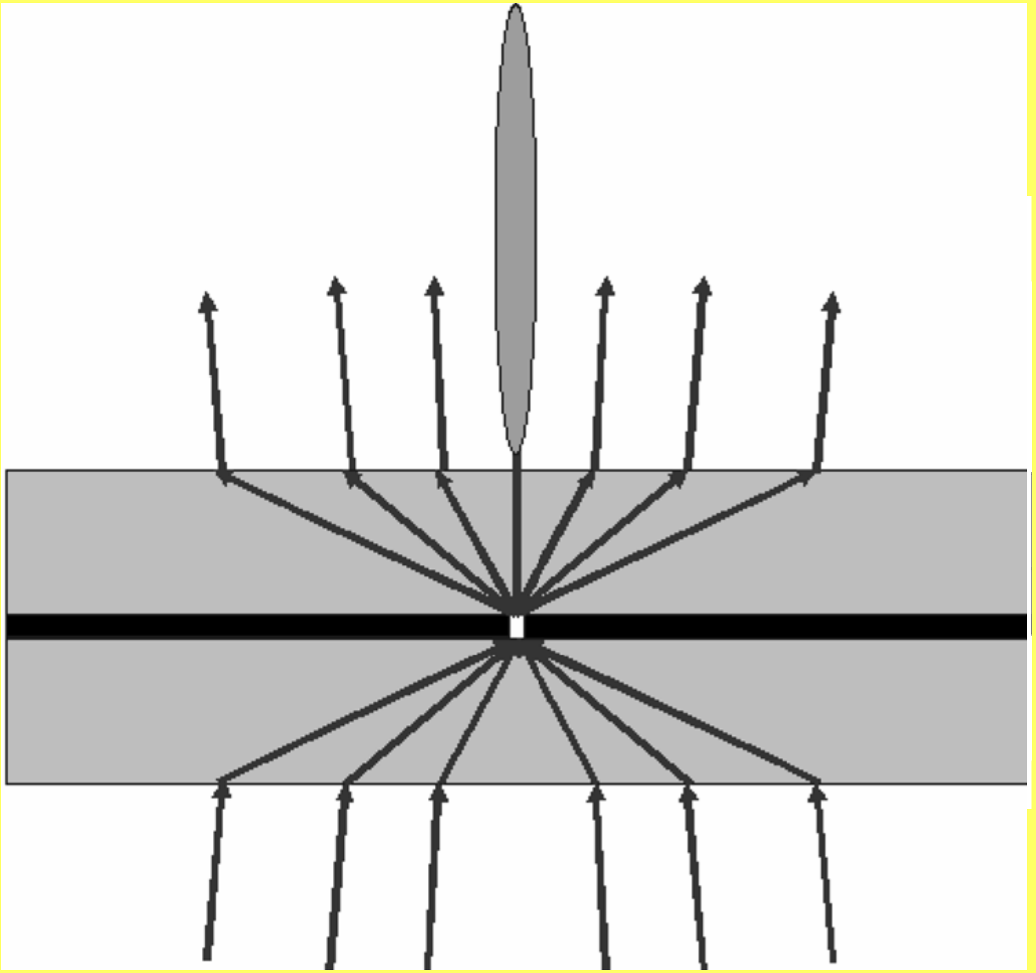
## Ring Cavity



# Sub-wavelength Transmission

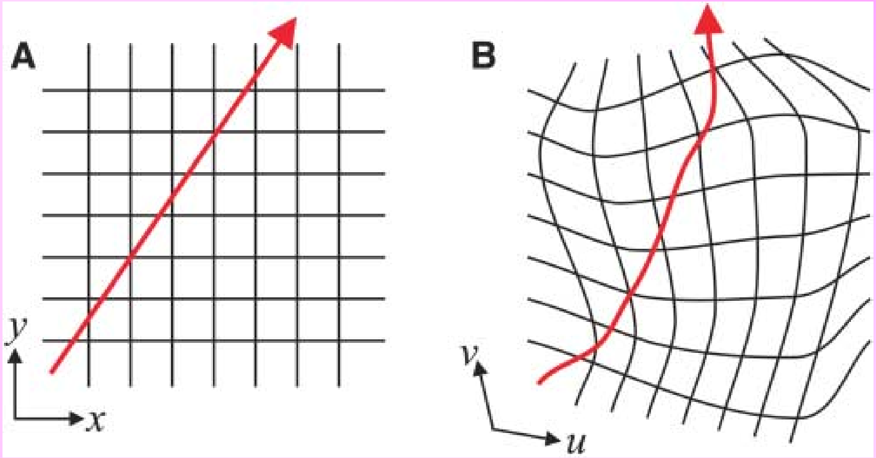


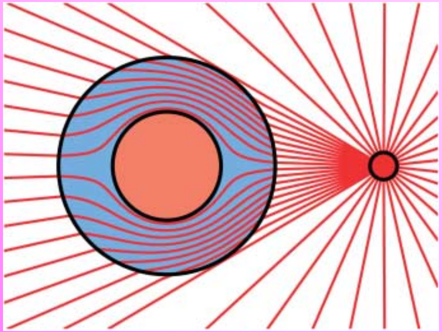
**Al, Bilotti, Engheta, Vegni, IEEE Trans. Ant. Prop. 54, 1632 (2006)**

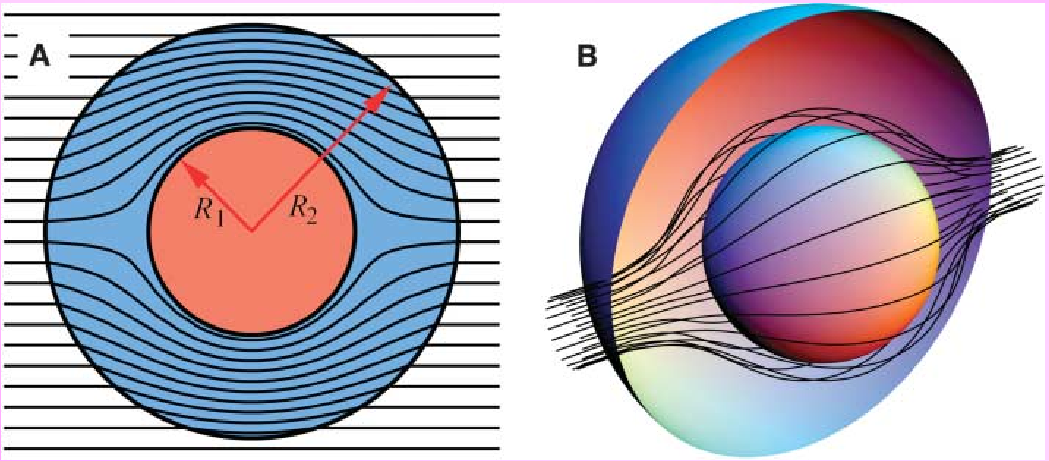
# Cloaking

0<n<1




Pulling and Stretching space






Pendry, Schurig, Smith, Science, 312, 1780 (2006).

# Conclusions

- Metamaterials have a promising and fascinating future
- 2D and 3D metamaterials with loss control will become mainstream
- Nonlinearity and tunability are in sight
- The race is on towards the visible and depends upon nano-technology


STOP