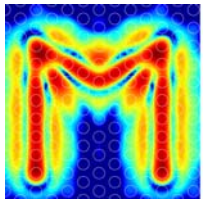
Near Field Imaging in  etamaterials

Anna Radkovskaya
Moscow State University
Department of Magnetism

WiP School Paris
14 April 2008

Near Field Imaging in Metamaterials

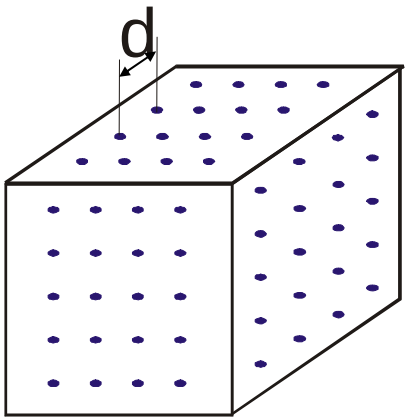
Contents

- Magnetic metamaterials
- Slow magnetoinductive waves
- Near field lens
- Towards optical frequencies: new features

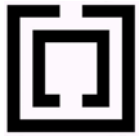
Magnetic metamaterials

Small metallic inclusions

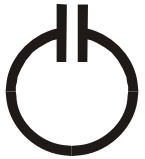
$d << \lambda$



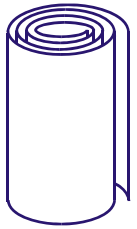
Elements must be resonant



Split Ring Resonator

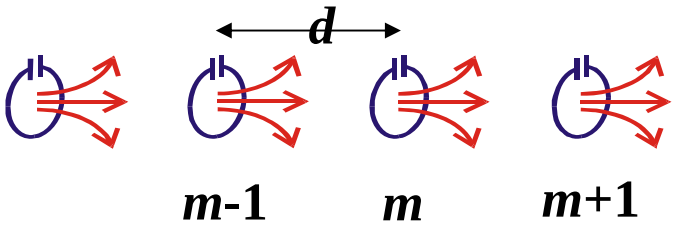


Capacitively Loaded Ring

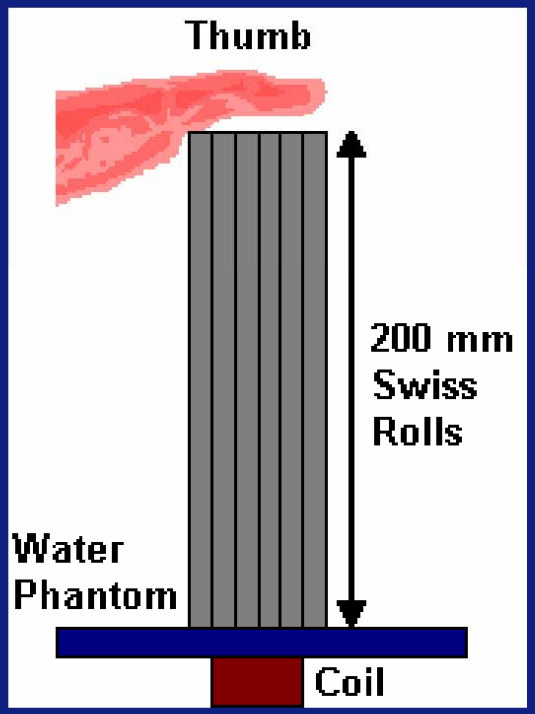


Swiss Roll

Coupling between elements: magnetoinductive (MI) waves



Swiss Rolls in MRI – first demonstration



Schematic layout

Without
Swiss Rolls

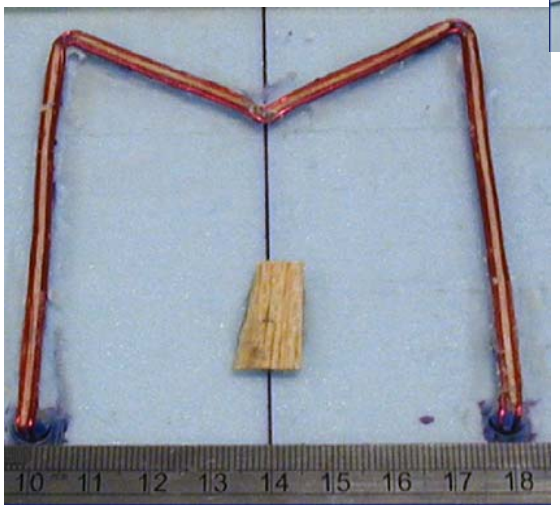
With
Swiss Rolls

- **Swiss Rolls acted as an RF Flux Duct, but all spatial information was obtained from the MRI encoding**

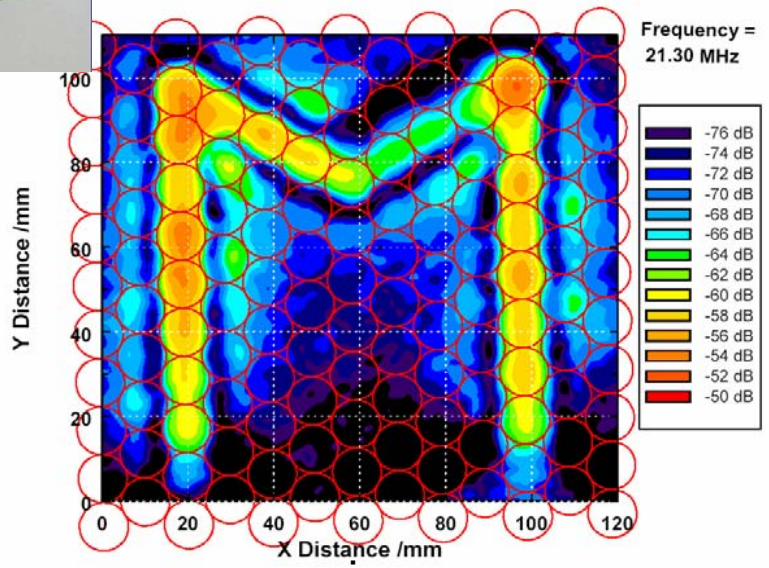
Wiltshire et al., Science 2001

Swiss Roll Near Field Lens

Wiltshire et al Opt. Expr. 2003
Pendry et al., Science 2004

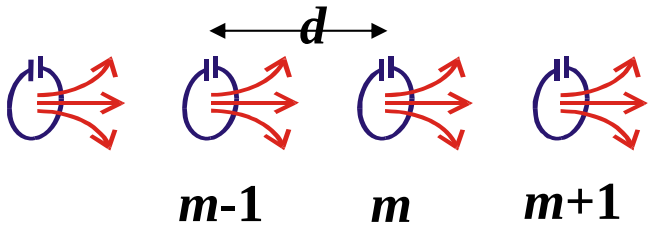


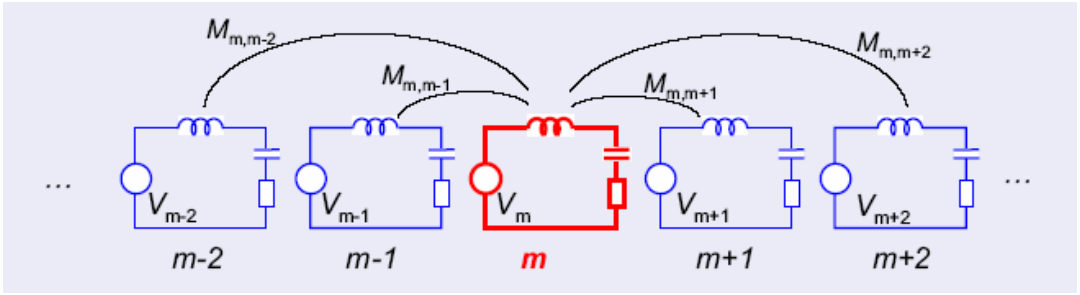
object



image

Interaction of elements: Magnetoinductive (MI) waves





Kirchhoff's Law:

$$\underbrace{\left[R + j\omega L\left(1 - \frac{\omega_0^2}{\omega^2}\right)\right]}_{\text{self-impedance}} I_m + \underbrace{j\omega M}_{\text{mutual impedance}} \left(I_{m-1} + I_{m+1}\right) = 0$$

Wave ansatz:

$$I_m = I_0 e^{\left[j(\omega t - mkd)\right]}$$

Dispersion:

$$1 - \frac{\omega_0^2}{\omega^2} + j\frac{R}{\omega L} + \frac{2M}{L}\cos kd = 0$$

coupling constant

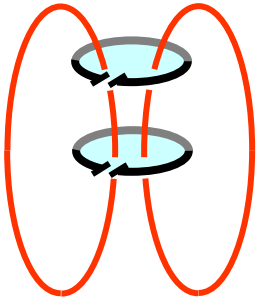
Shamonina et al., Electr.Lett. 2002
Shamonina et al., J. Appl. Phys. 2002

Interaction of elements: Magnetoinductive (MI) waves

coupling constant

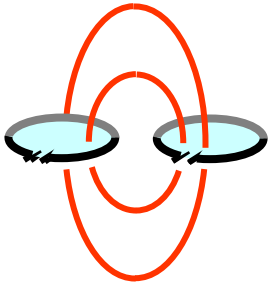
Dispersion: $$1-\frac{\omega_0^2}{\omega^2}+j\frac{R}{\omega L}+\frac{2M}{L}\cos kd=0$$

axial structure

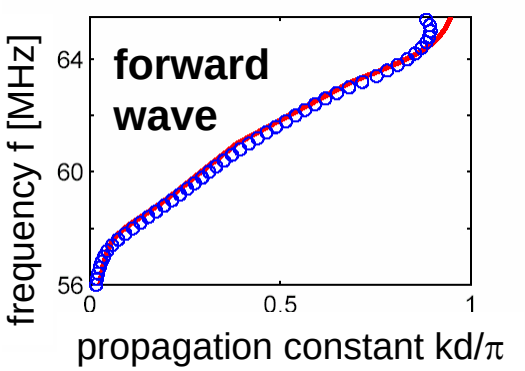


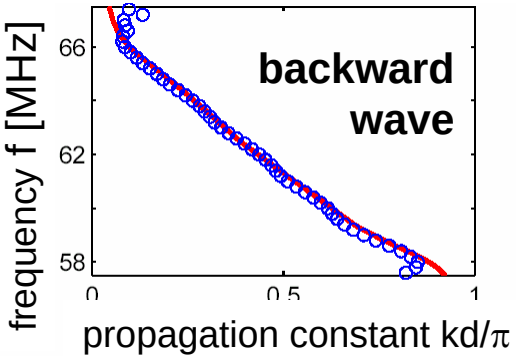
M > 0

planar structure



M < 0



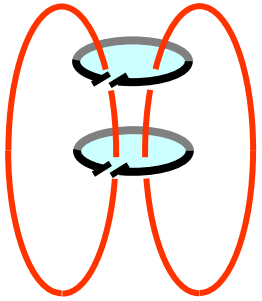


Shamonina et al., J. Appl. Phys. 2002
Wiltshire et al.. Electr. Lett. 2003

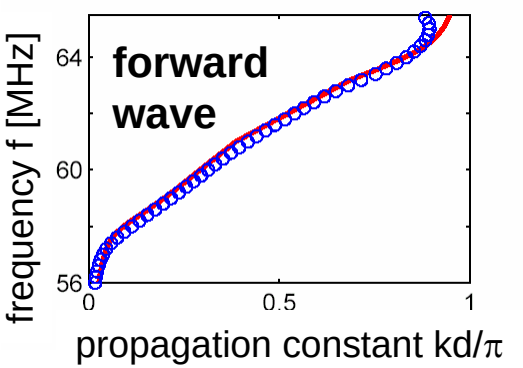
Interaction of elements: Magnetoinductive (MI) waves

- Slow waves (phase velocity smaller than c)
- Short wavelengths, Large k components
- Can couple to and influence the near field

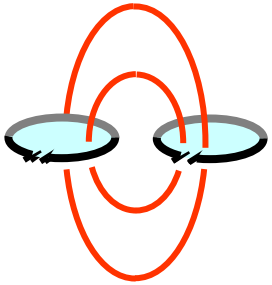
axial structure



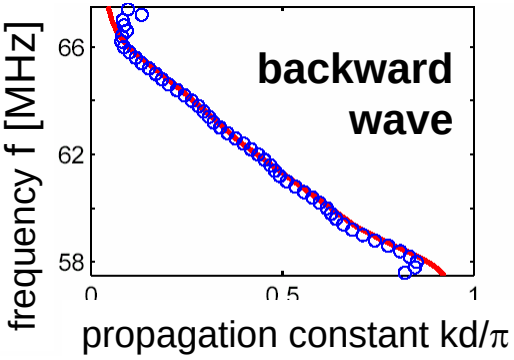
M > 0



planar structure

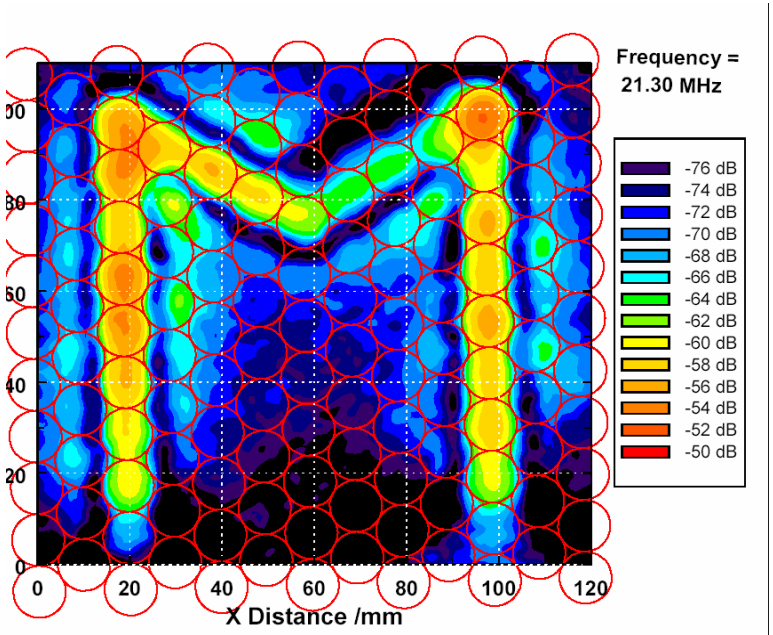


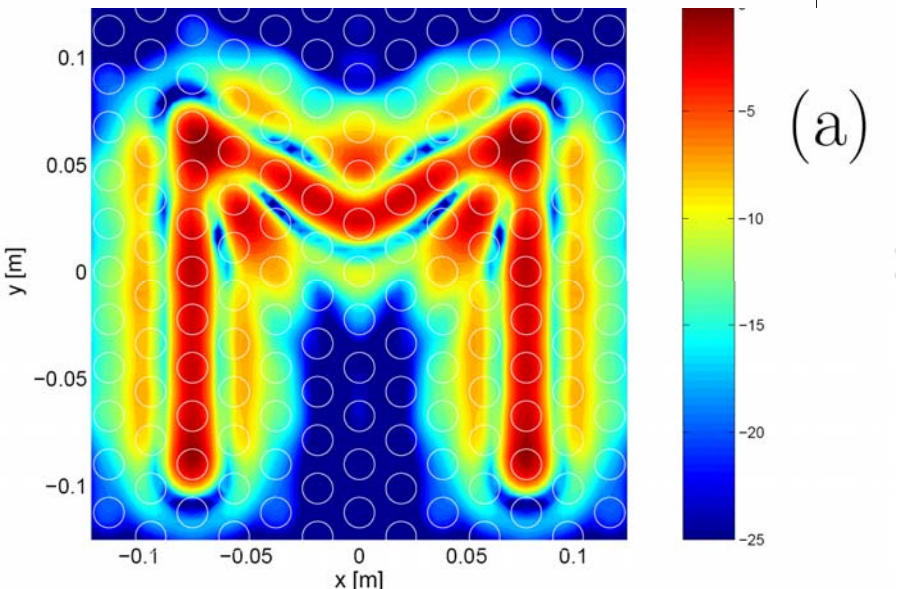
M < 0



Shamonina et al., J. Appl. Phys. 2002
Wiltshire et al.. Electr. Lett. 2003

Swiss Roll Near Field Lens

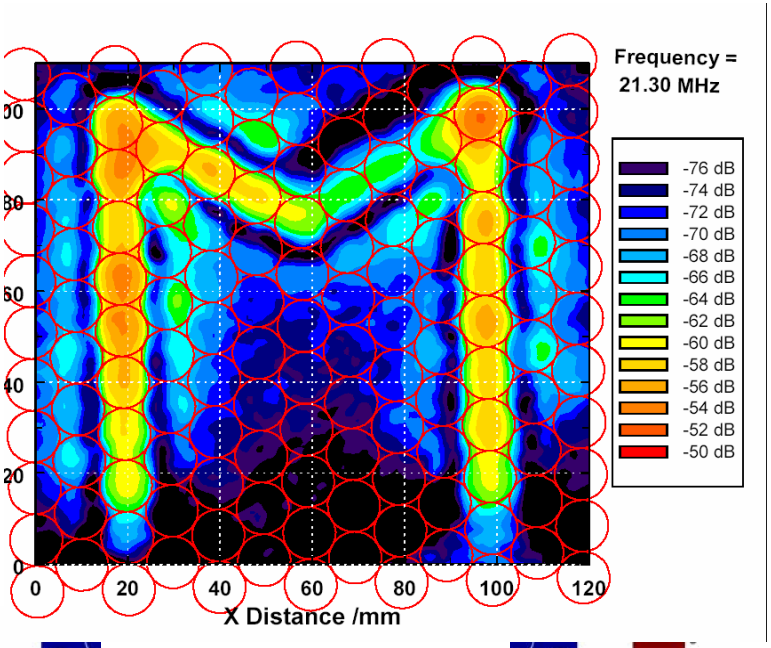




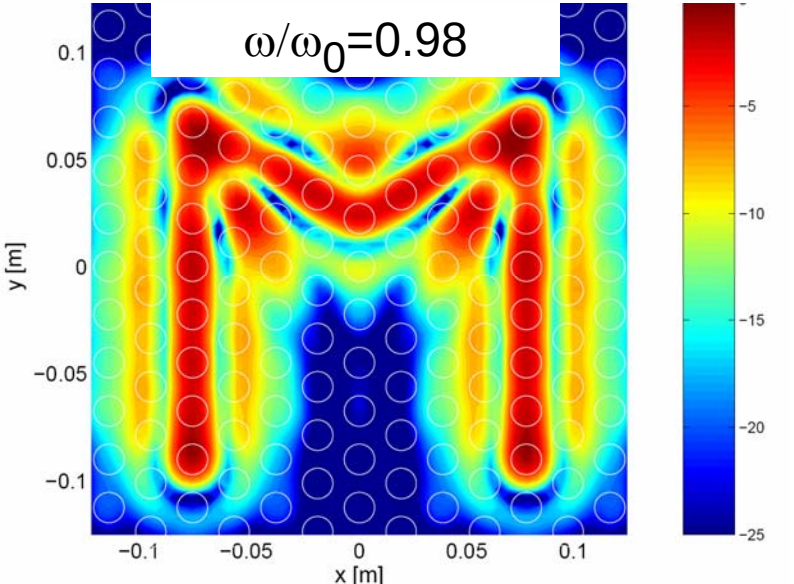
Wiltshire et al., Optics Express 2003
Pendry et al., Science 2004

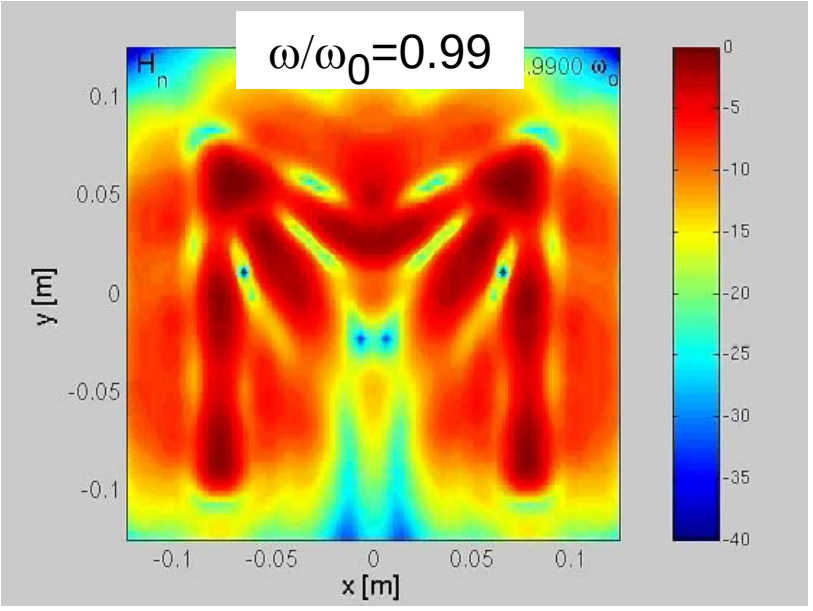
Zhuromskyy et al., Optics Express 2005

Swiss Roll Near Field Lens

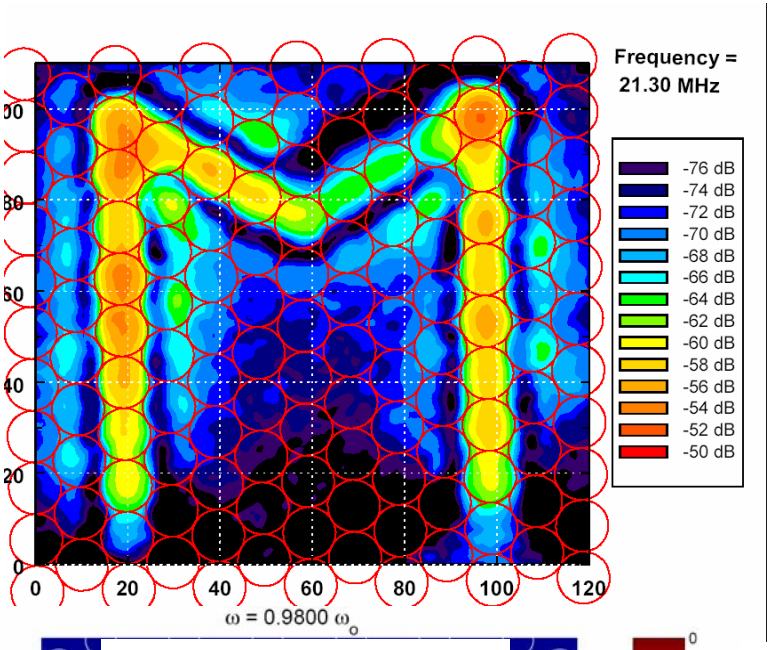


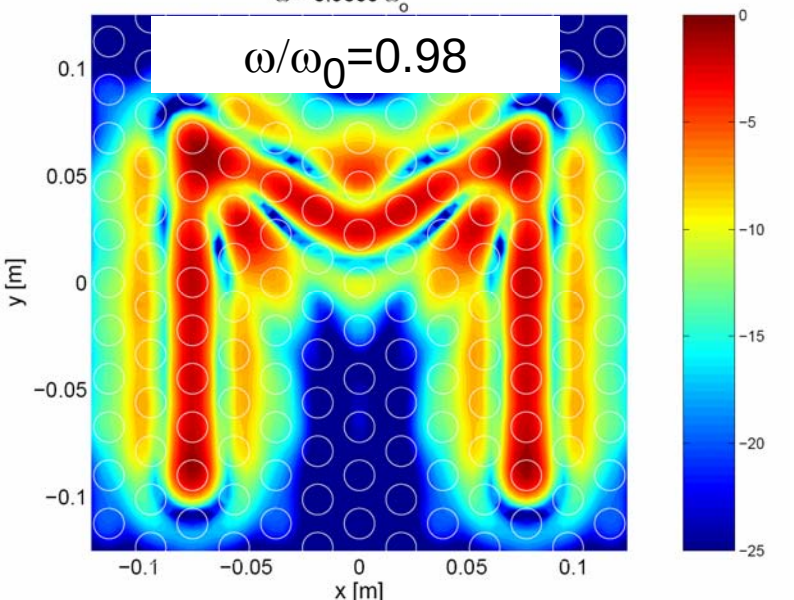
Zhuromskyy et al., Optics Express 2005



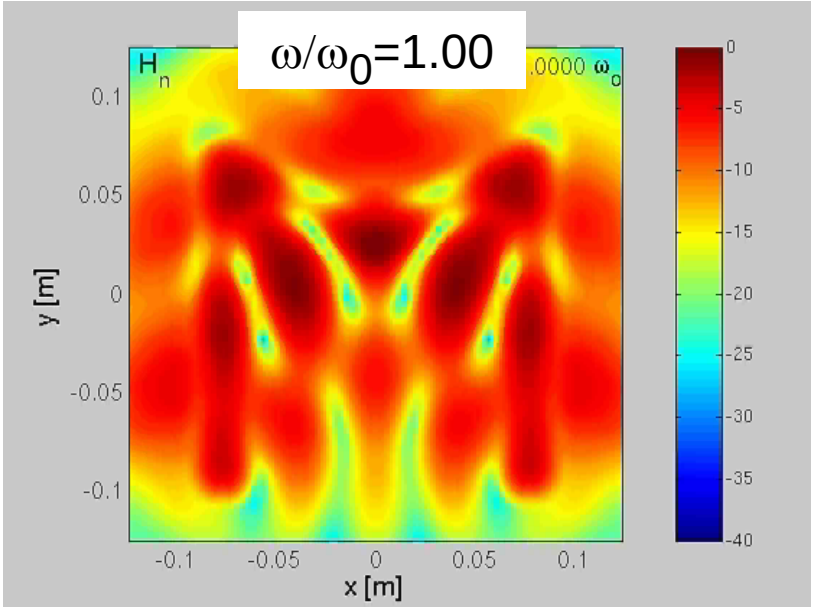


Swiss Roll Near Field Lens

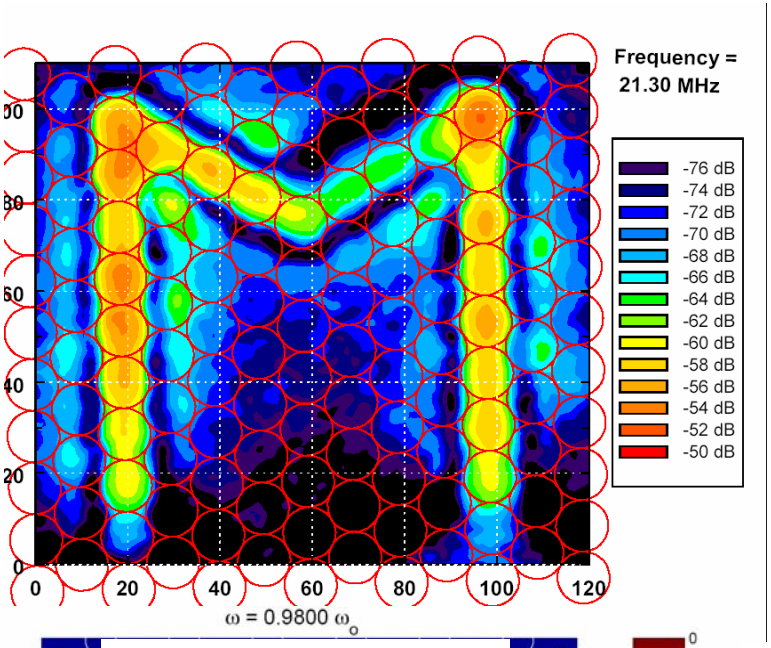


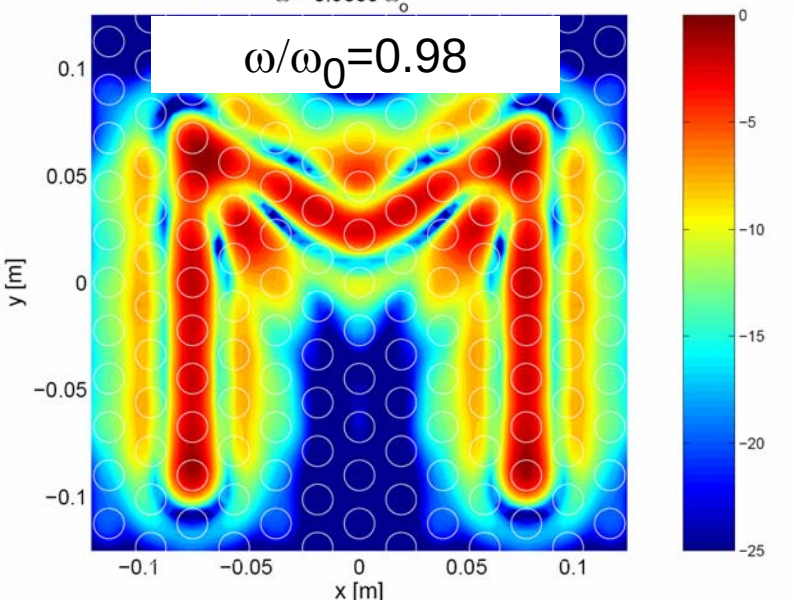


Zhuromskyy et al., Optics Express 2005

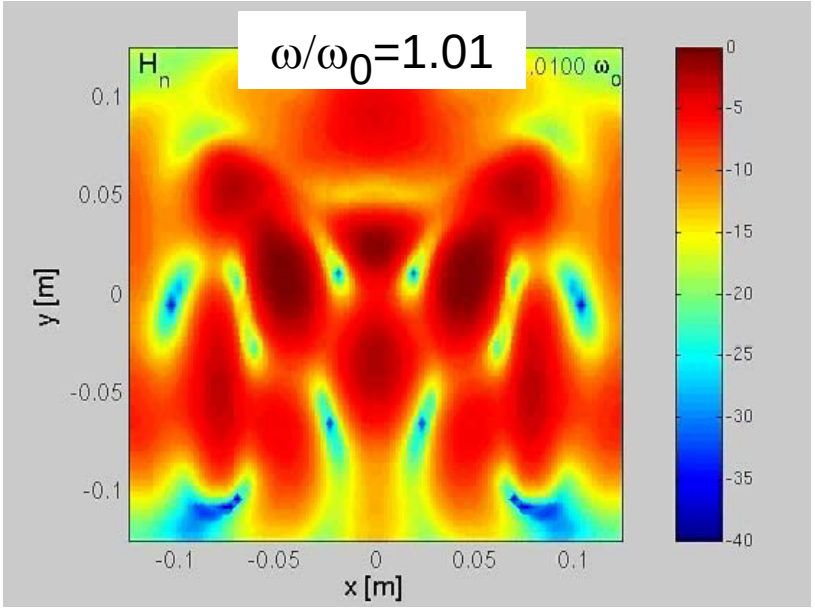


Swiss Roll Near Field Lens

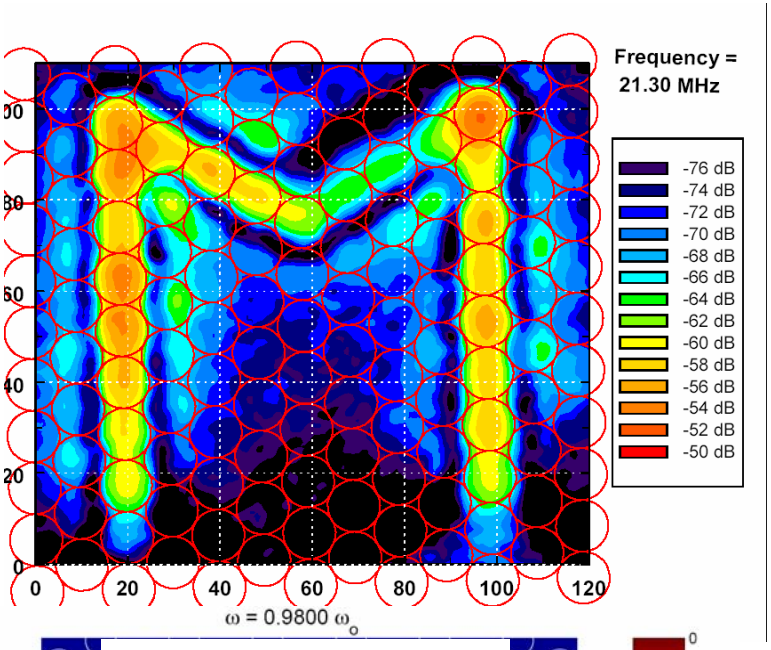


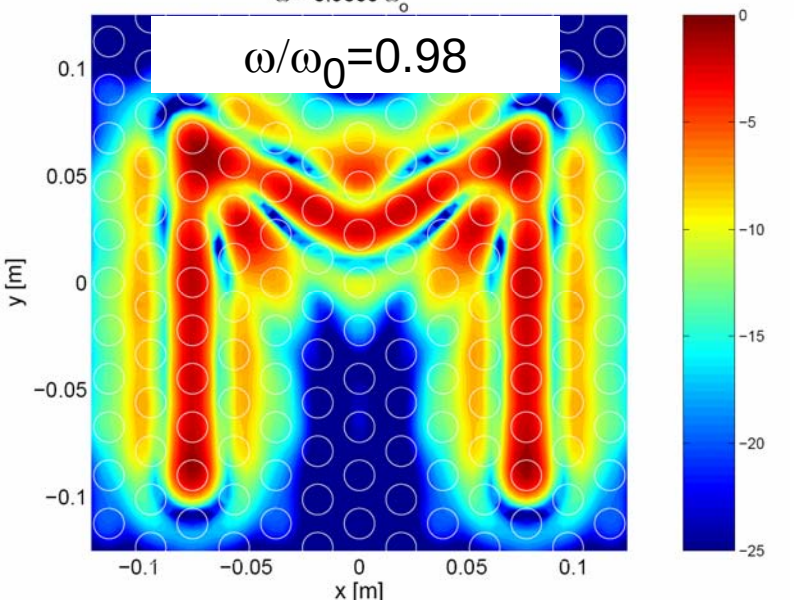


Zhuromskyy et al., Optics Express 2005

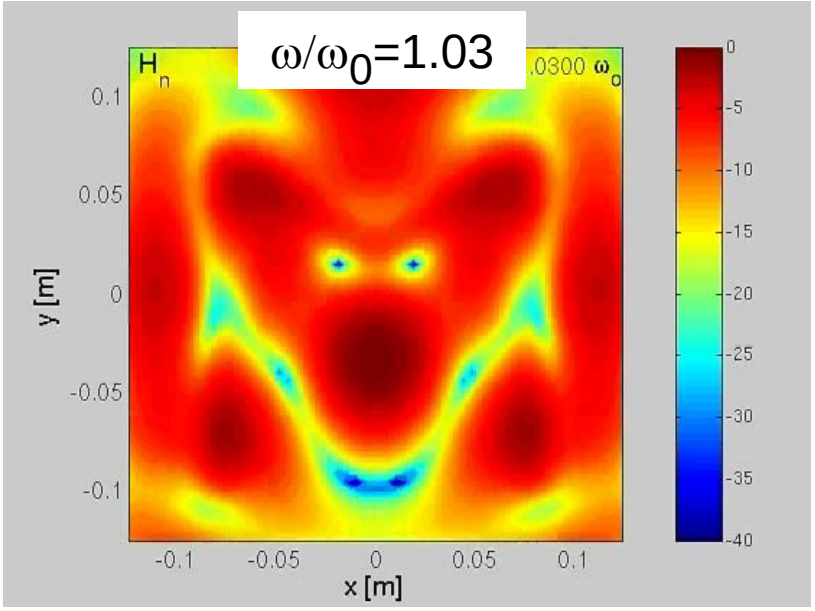


Swiss Roll Near Field Lens

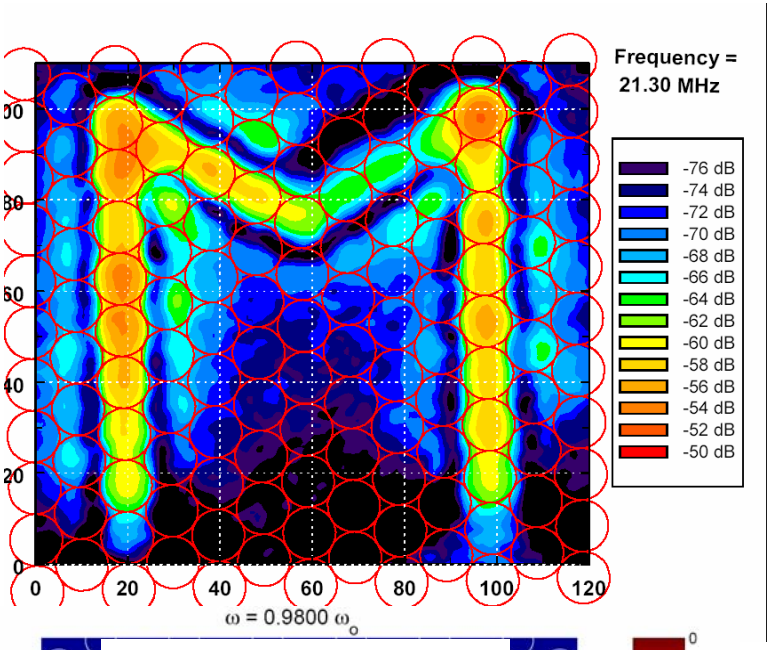


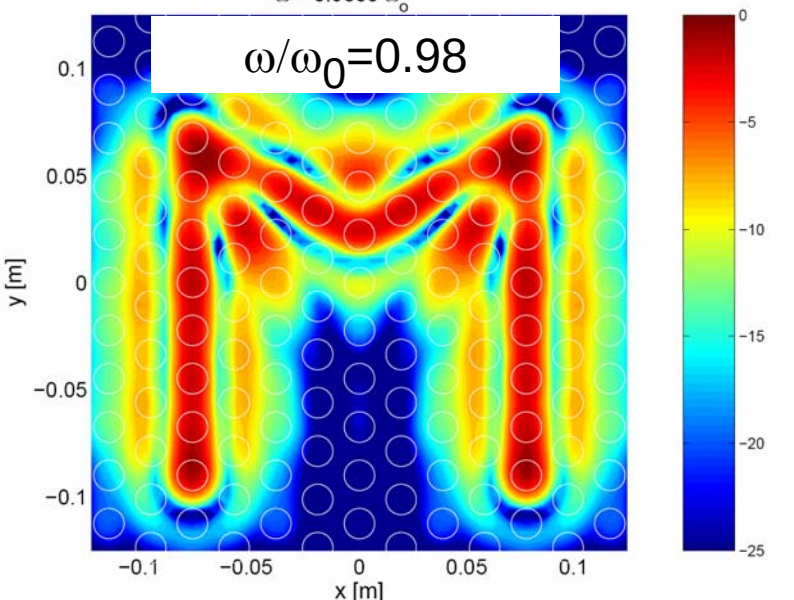


Zhuromskyy et al., Optics Express 2005

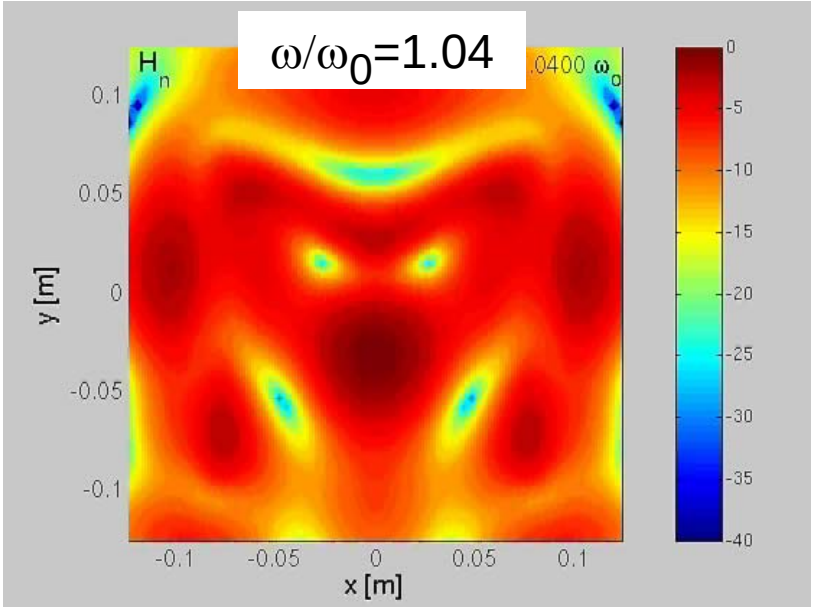


Swiss Roll Near Field Lens

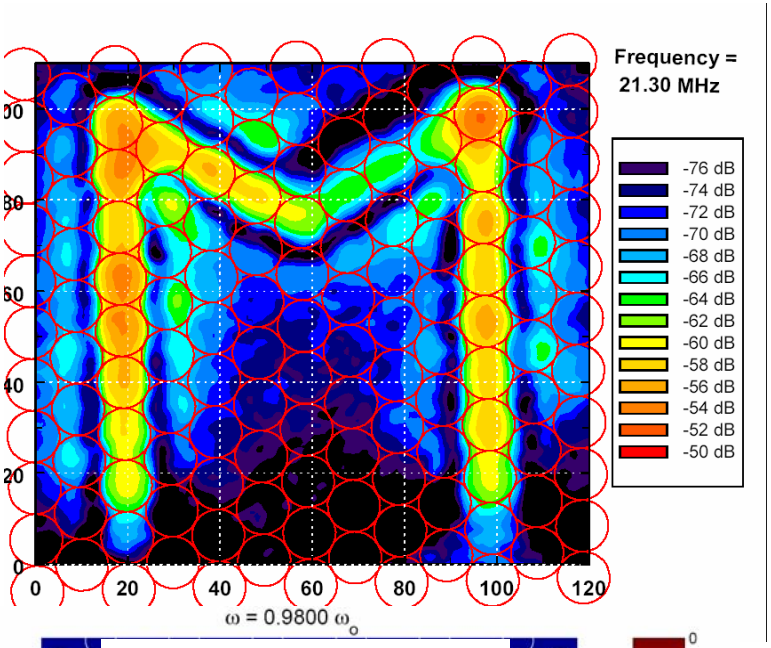


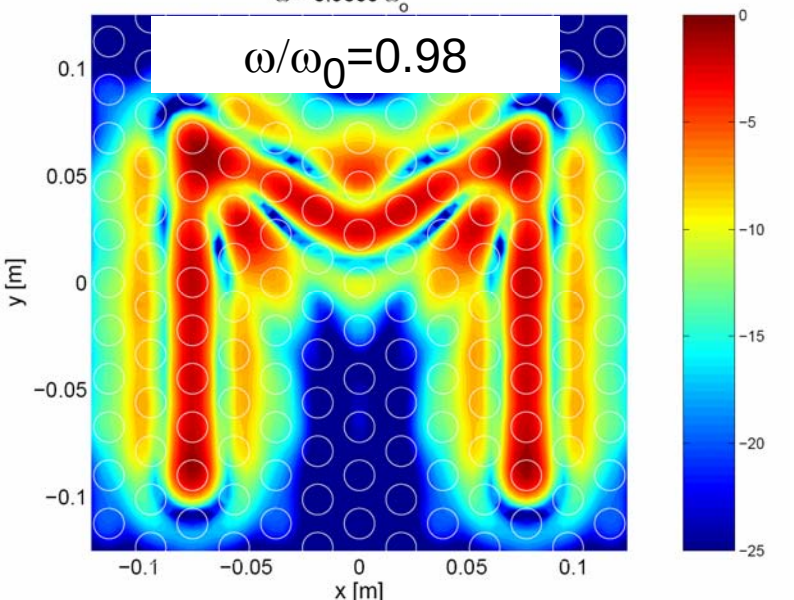


Zhuromskyy et al., Optics Express 2005

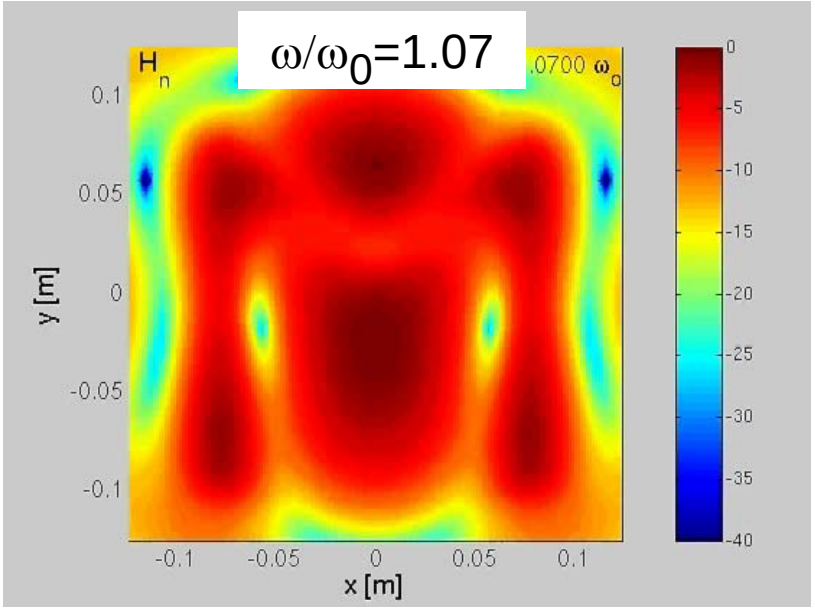


Swiss Roll Near Field Lens

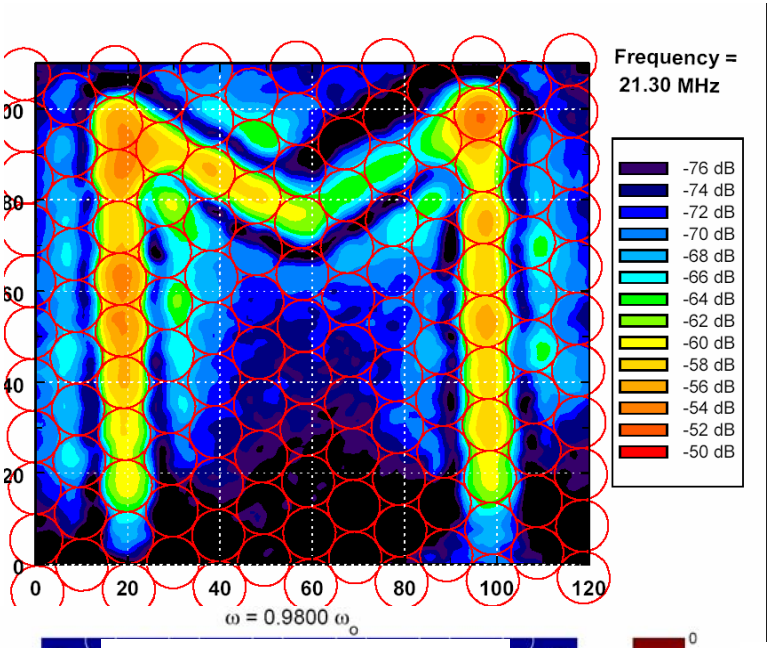


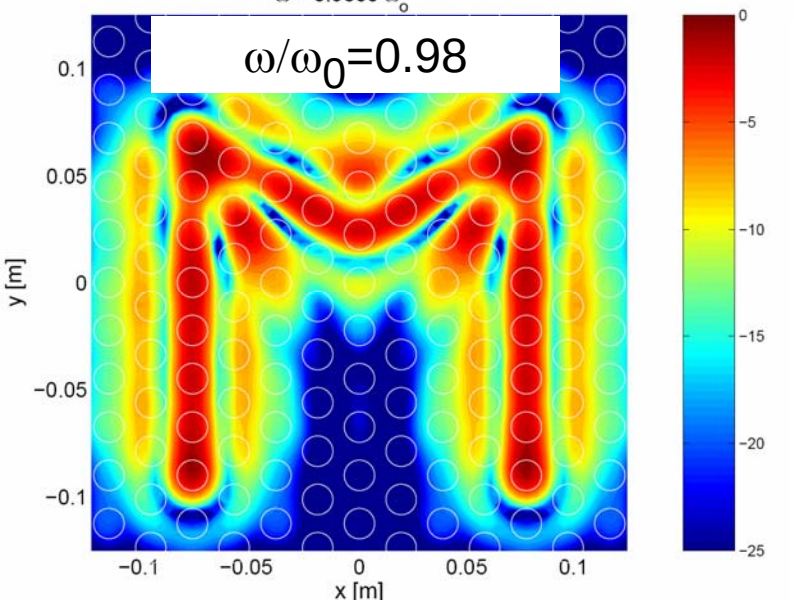


Zhuromskyy et al., Optics Express 2005

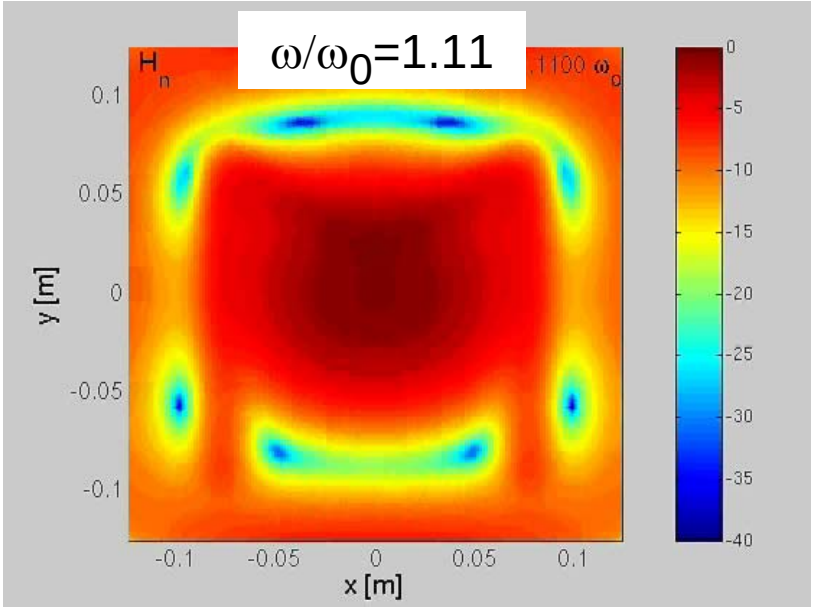


Swiss Roll Near Field Lens

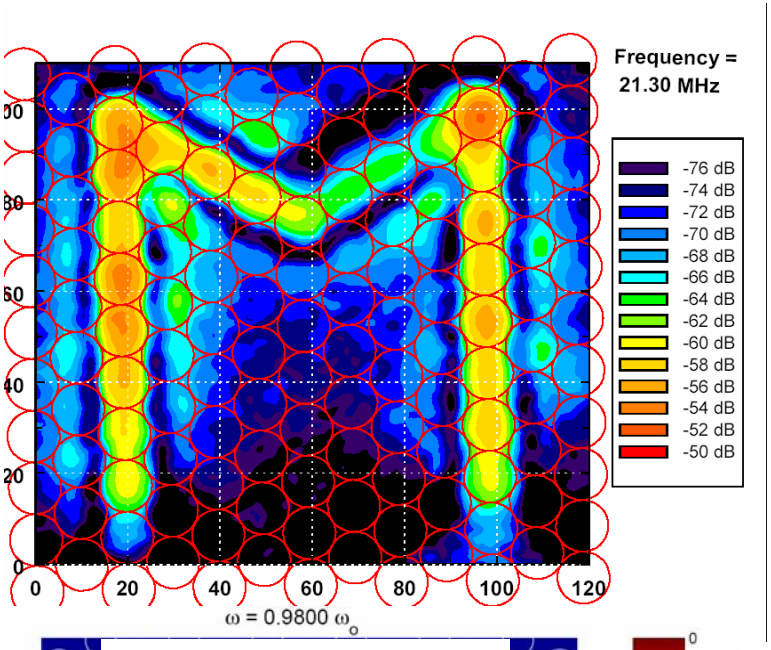


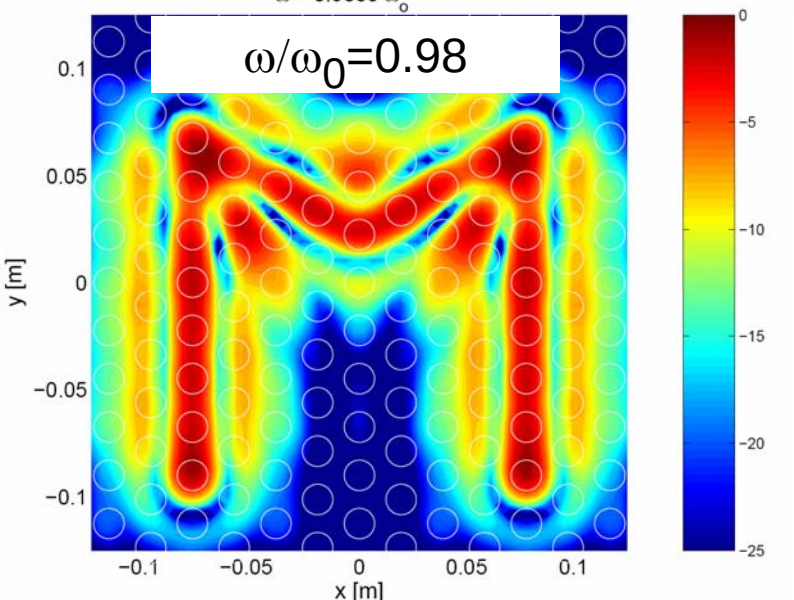


Zhuromskyy et al., Optics Express 2005

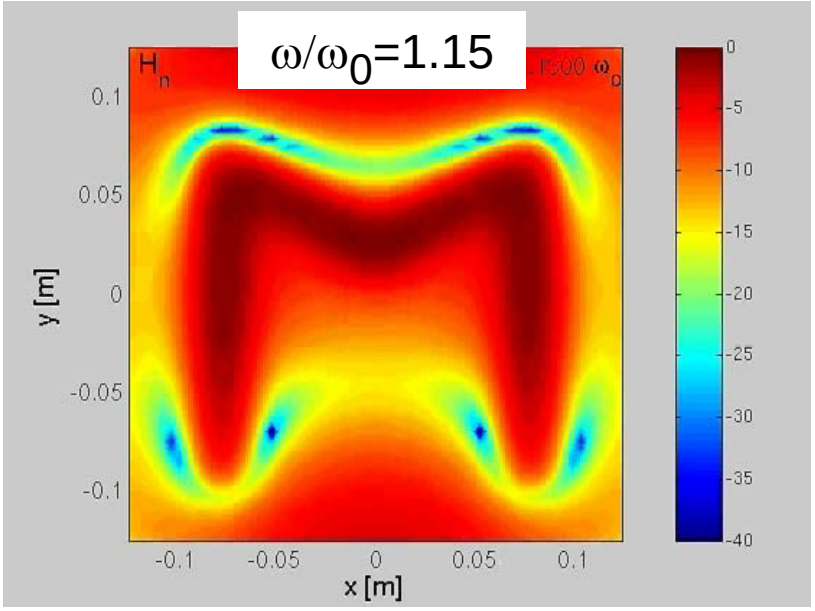


Swiss Roll Near Field Lens

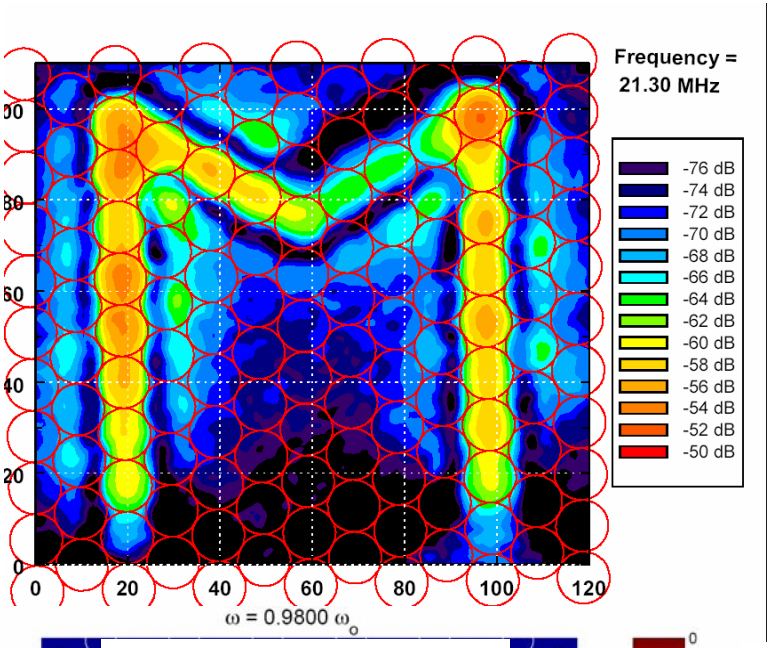


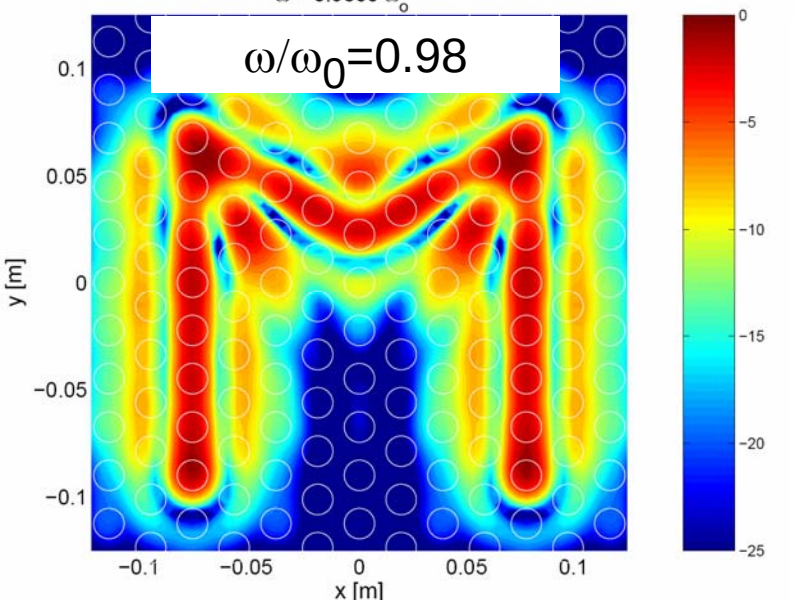


Zhuromskyy et al., Optics Express 2005

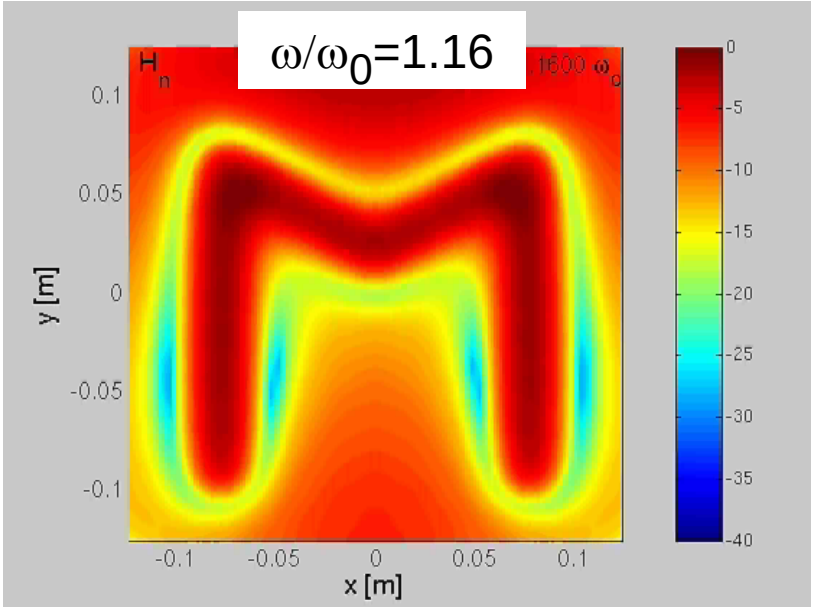


Swiss Roll Near Field Lens

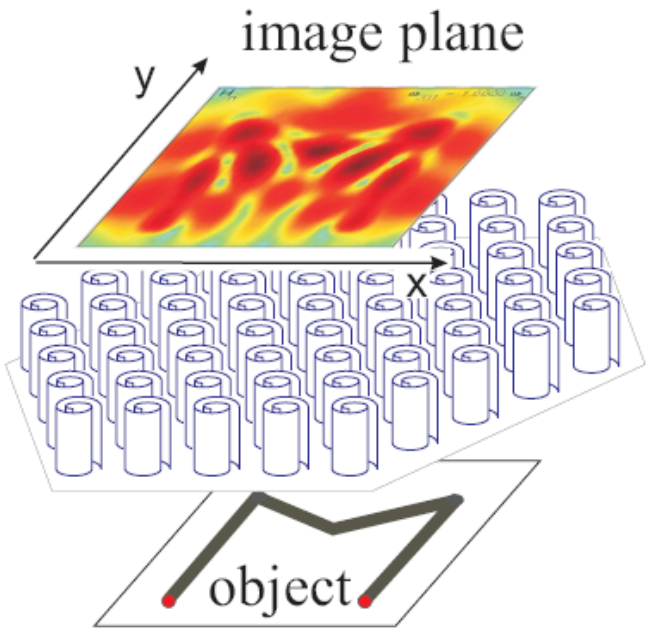


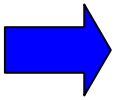


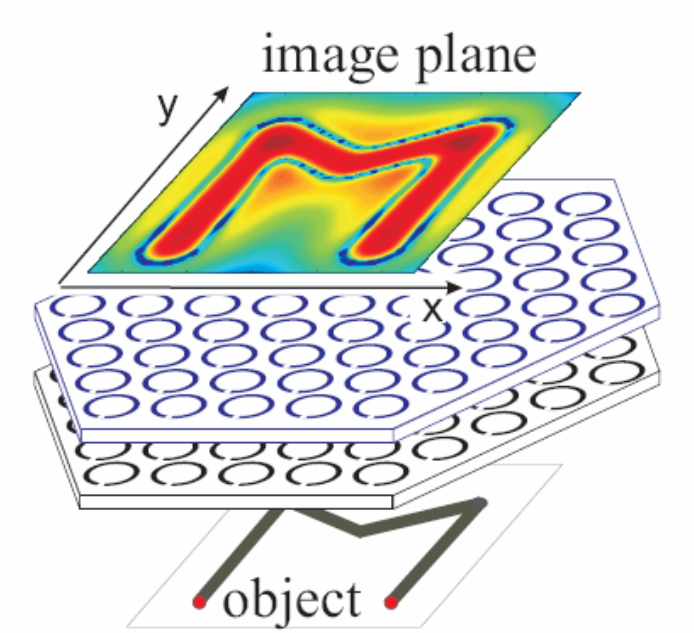
Zhuromskyy et al., Optics Express 2005



Near Field Magnetoinductive Lens





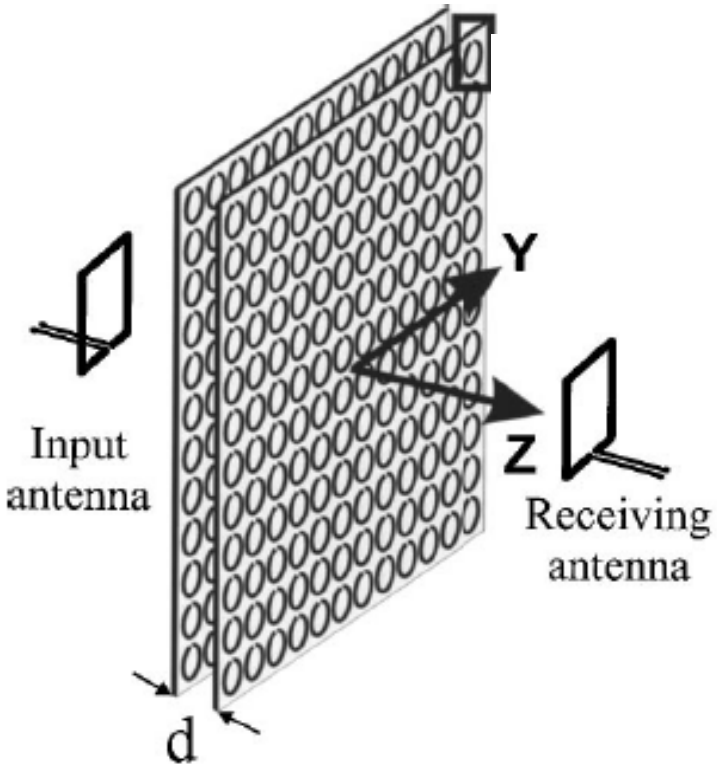


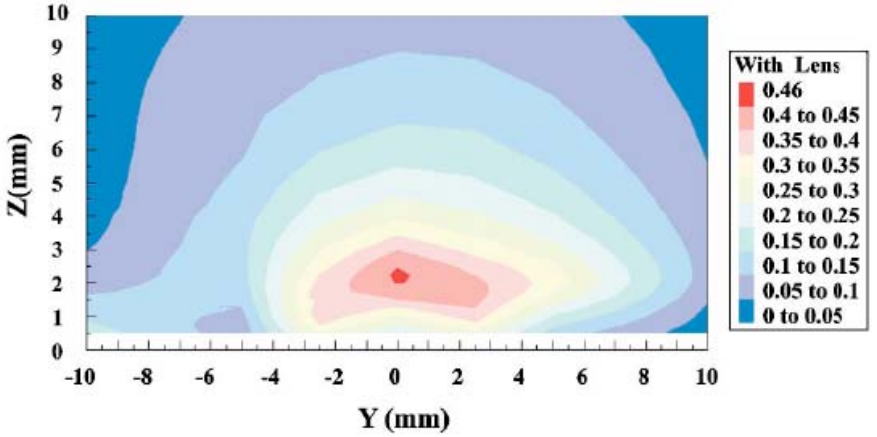
• No sub-λ-imaging around the resonance frequency

Freire and Marques, Appl. Phys. Lett. (2005)

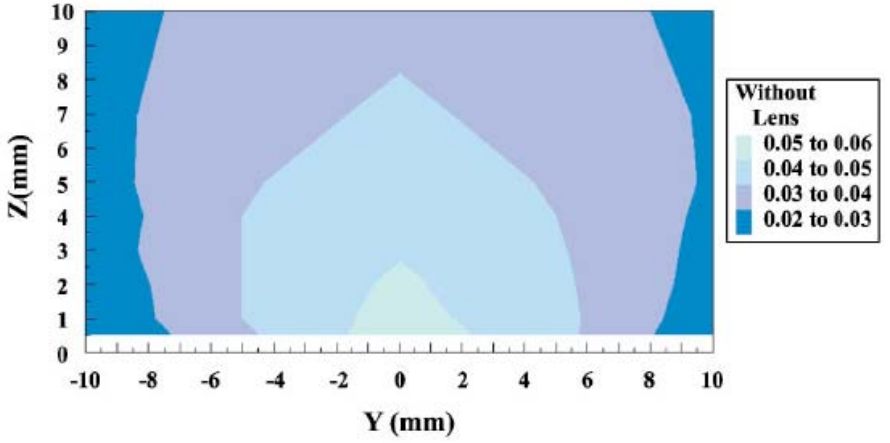
“A planar magneto-inductive lens for three-dimensional subwavelength imaging”

Freire and Marques, Appl. Phys. Lett. 86, 182505, 2005





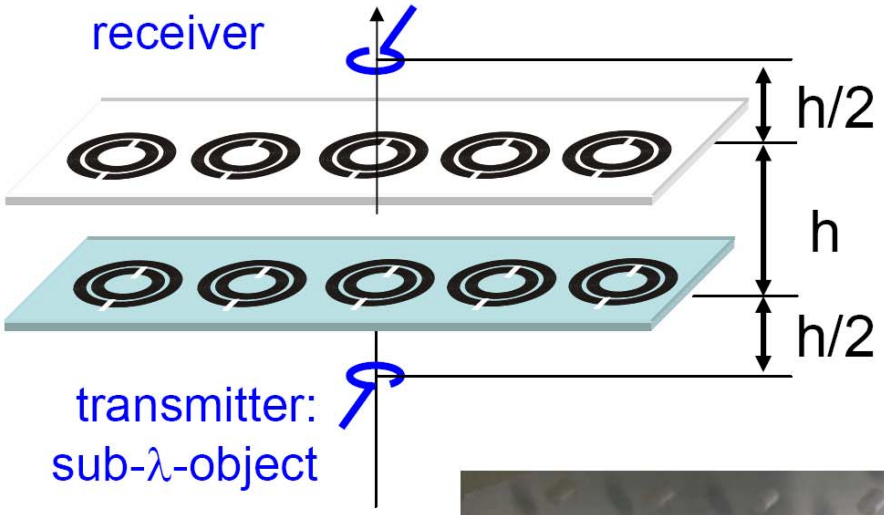
(a)

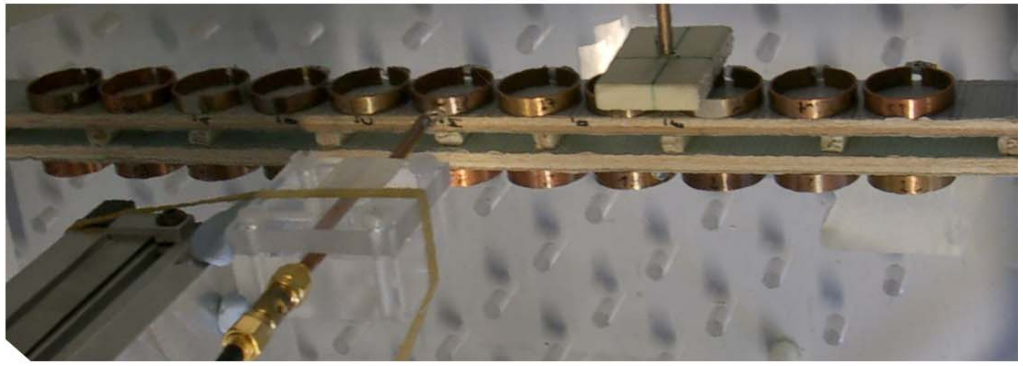


(b)

Near Field Magnetoinductive Lens

The mechanism?



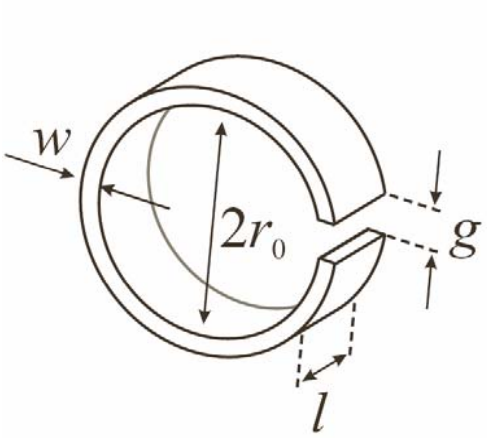


Sydoruk et al. J. Appl. Phys. (2007)

Experiment: Radkovskaya (Moscow, Oxford)

The resonant elements of the lens: split pipes

r_0 = 10 mm
w = 1 mm
g = 1 mm
l = 5 mm
f_0 = 46.2 MHz
Q = 105



(a)

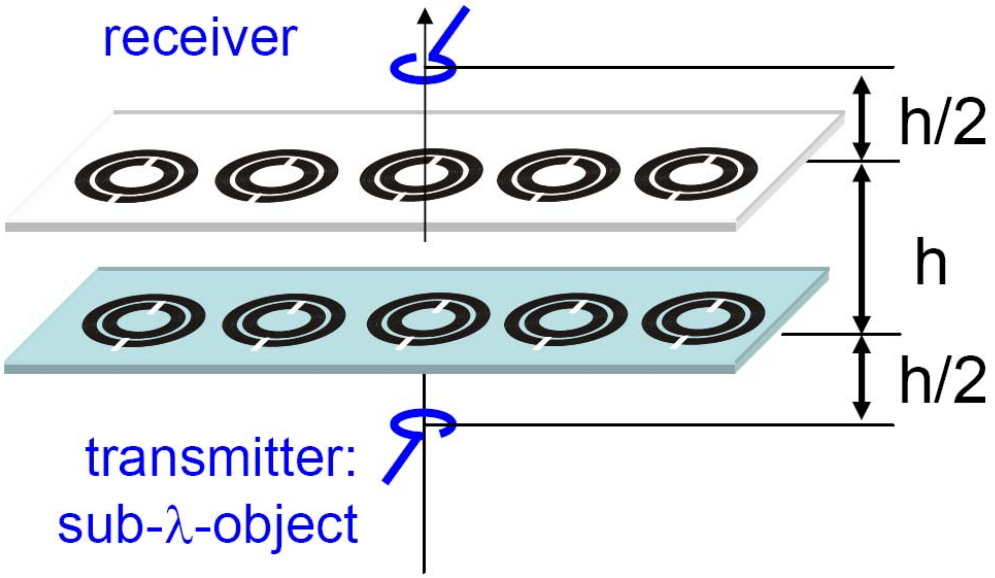
(b)

Sydoruk et al. J. Appl. Phys. (2007)

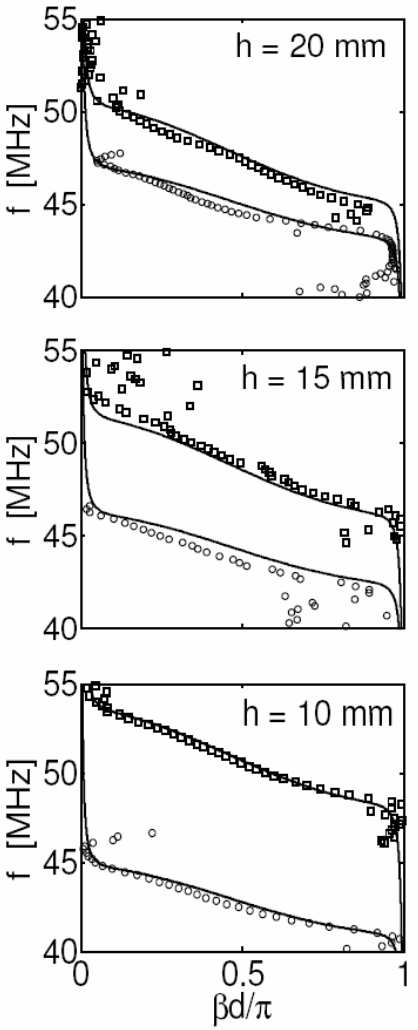
Experiment: Radkovskaya (Moscow, Oxford)

Near-field Magnetoinductive Lens

The mechanism?



Dispersion relations: theory and experiment



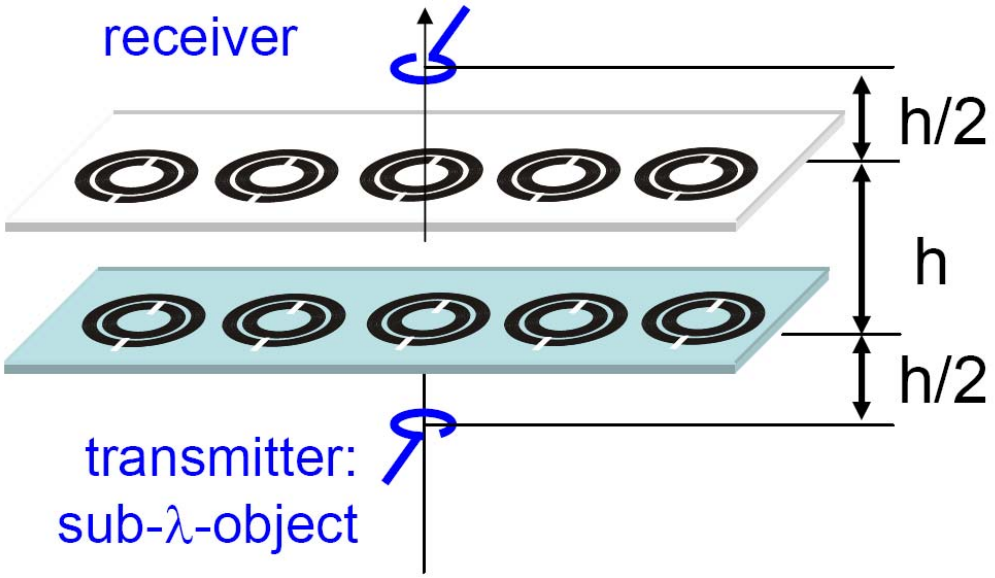
- coupled waveguide modes on both surfaces
- passband splits into two branches

Experiment: Radkovskaya (Moscow, Oxford)

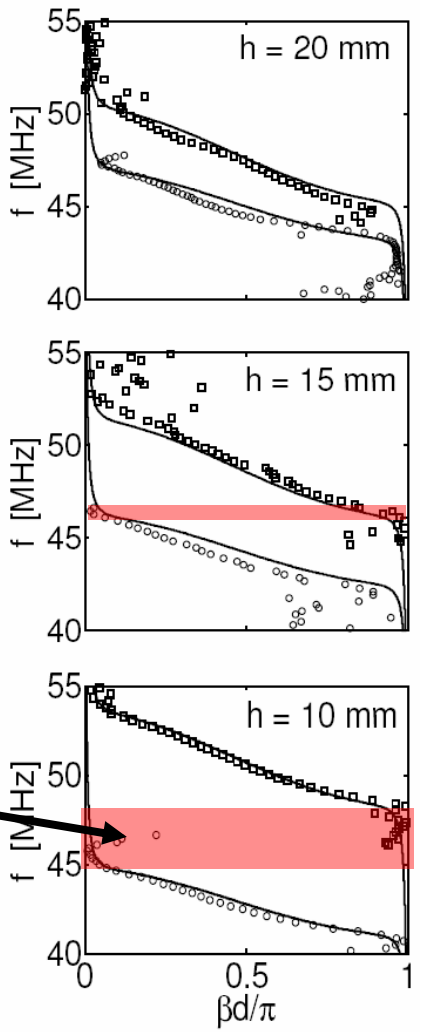
Sydoruk et al. Phys. Rev. B (2006)

Near-field Magnetoinductive Lens

The mechanism?



Dispersion relations: theory and experiment

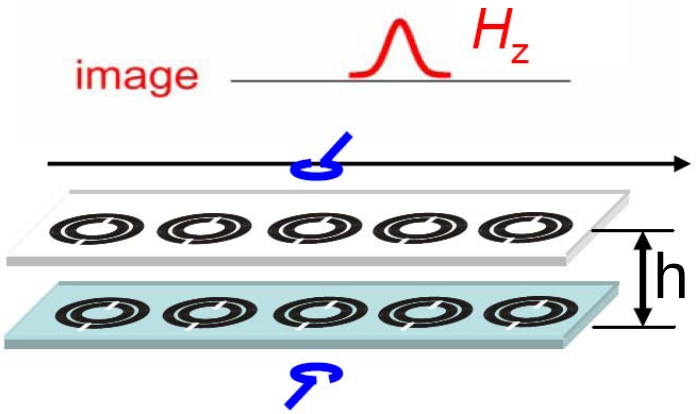


- coupled waveguide modes on both surfaces
- passband splits into two branches
- stopband: no broadening of the image
- sub-λ-imaging

Experiment: Radkovskaya (Moscow, Oxford)

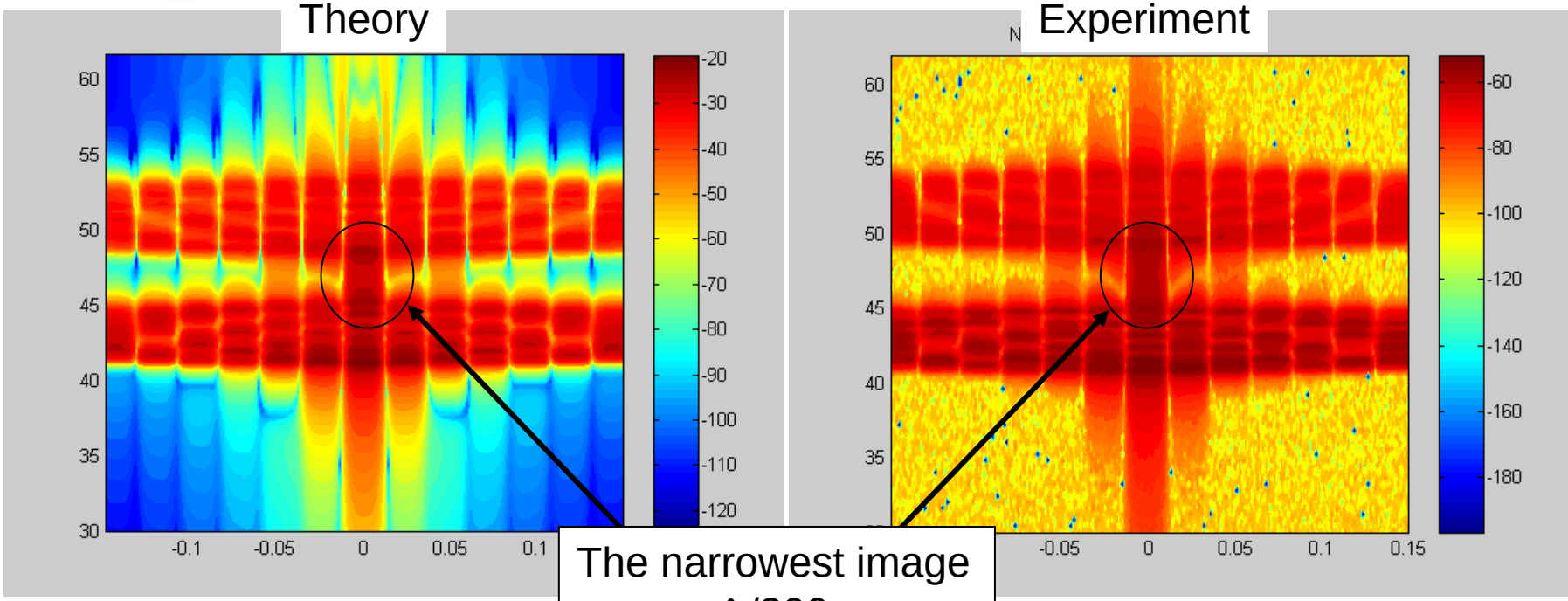
Sydoruk et al. Phys. Rev. B (2006)

Near-field MI lens: theory and experiment



2 layers x 11 split pipes
h=10mm, r_0=10mm, f_0=46 MHz

Image width vs. frequency



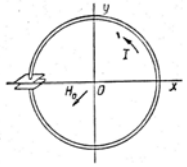
Experiment: Radkovskaya (Moscow, Oxford)

Sydoruk et al. J. Appl. Phys. (2007)

Outlook: Nanostructured metamaterials

MHz-elements

Capacitive loops



1952 Schelkunoff & Friis

2002 Wiltshire

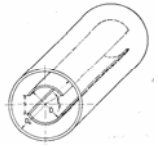
2005 Radkovskaya

“Swiss Rolls”

1999 Pendry et al.

GHz-elements

Split Ring Resonators



1977
Schneider &
Dullenkopf

1981
Hardy & Whitehead

1999
Pendry et al.

THz-Elements

Nano-U

2005 Podolskiy et al.
2005 Enkrich et al.

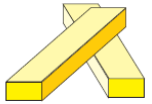
Nano-Crescents

2005 Shumaker-Parry
et al.

Pairs of nanorods

2002 Podolskiy et al.
2002 Panina et al.

Pairs of nano-stripes



2001 Svirko et al.

MHz-Elements

Capacitively loaded loops

or

Swiss Rolls

Wiltshire et al. El. Lett. 2003, JAP 2003

radius r ~ 1 cm

frequency f ~ 20 MHz
wavelength λ ~ 15 m

near field

no retardation

Near field coupling:
magnetic

GHz and THz-Elements

Split Ring Resonators

Radkovskaya et al. JMMM 2006
Hesmer et al., phys. stat. sol. b 2007

radius r ~ 1 cm

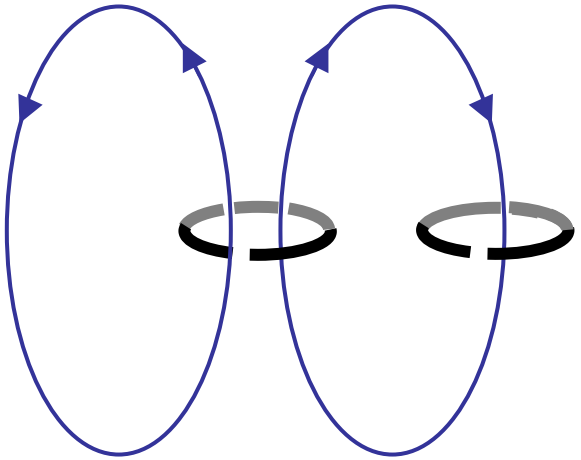
frequency f ~ 2 GHz
wavelength λ ~ 15 cm

far field

retardation is important!

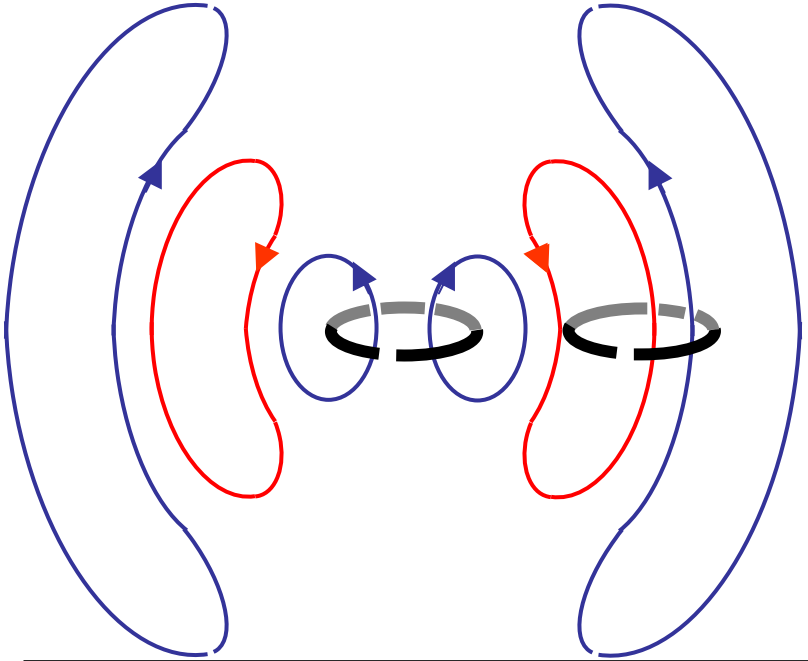
Coupling:
magnetic and electric!

No retardation: near field



coupling constant
- **real**
- **declines with distance as d^{-3}**

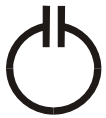
Retardation: far field



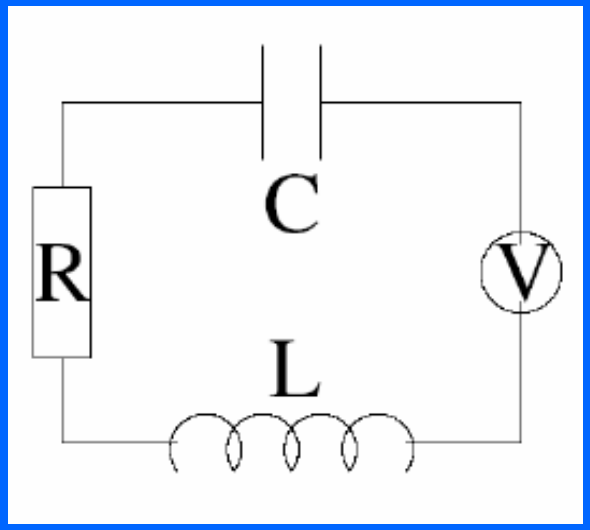
coupling constant
- **complex**
- **declines with distance slowly (d^{-1}, d^{-2}, d^{-3} terms)**

Radkovskaya et al. JMMM 2006
Hesmer et al., phys. stat. sol. b 2007

MHz-Elements

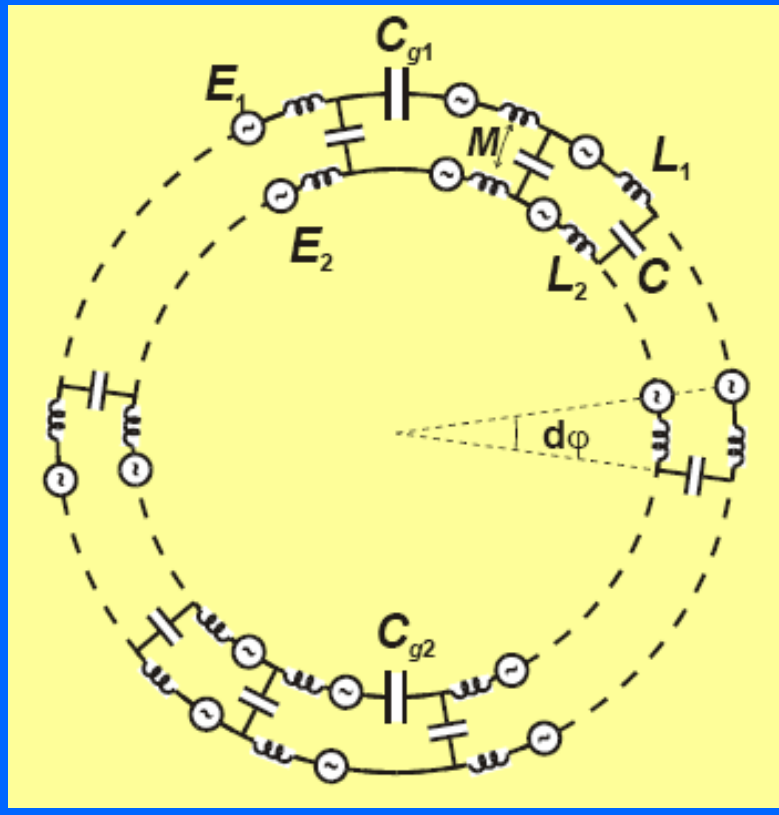


Equivalent circuit



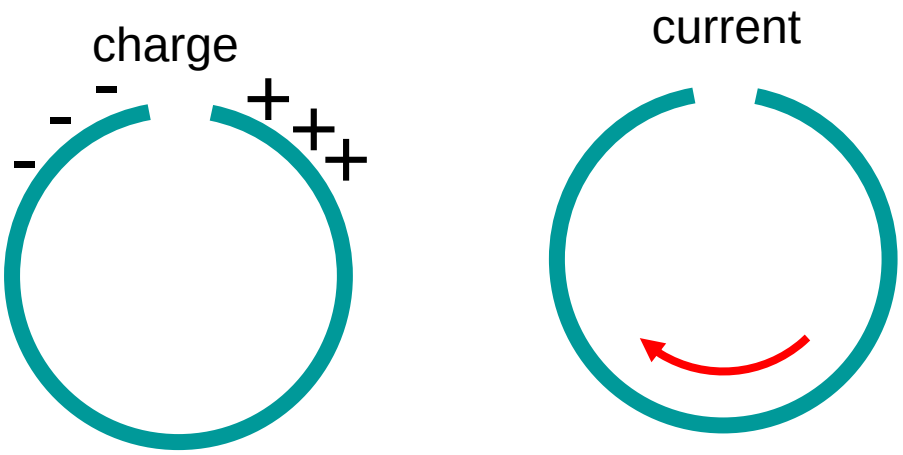
GHz-Elements

Equivalent circuit

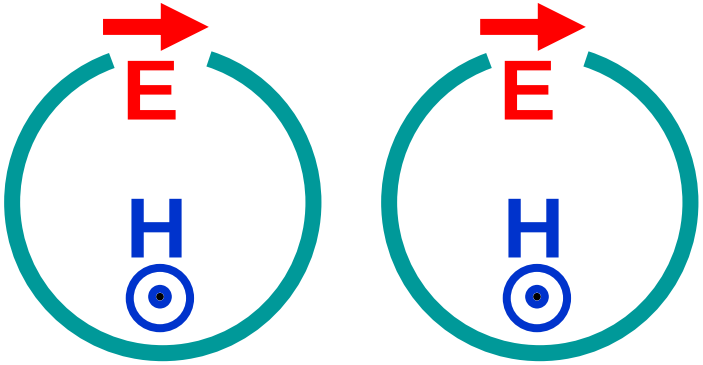


M. Shamonin et al., J. Appl. Phys. 2004

Near field coupling

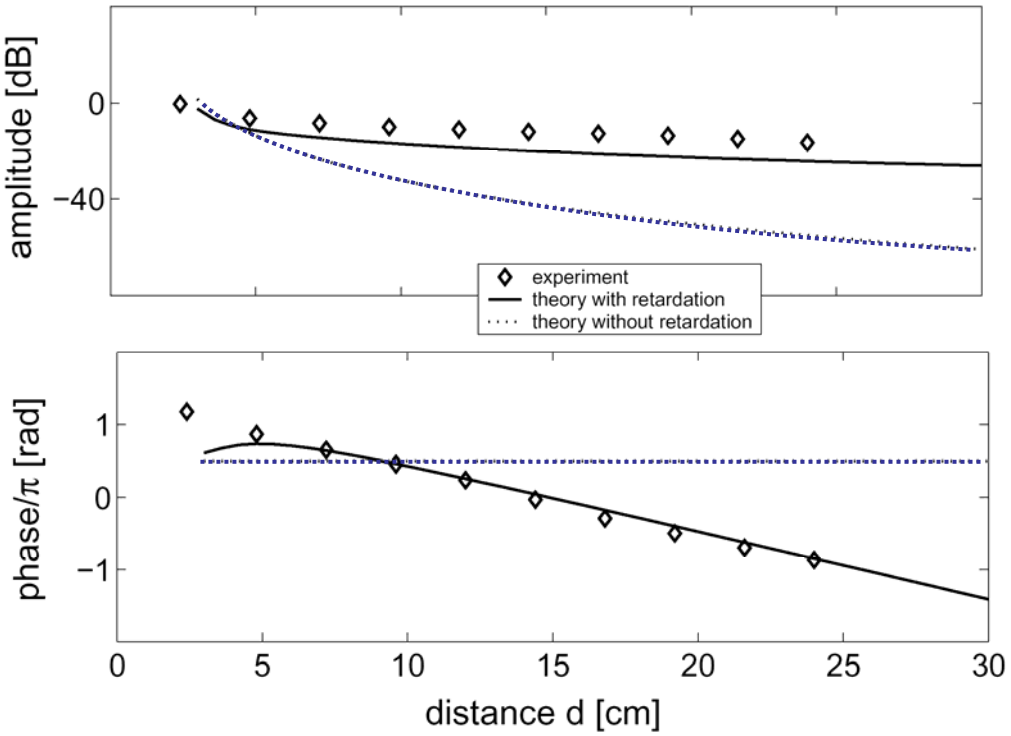


Electric and/or magnetic coupling?
Depends very much on the orientation!



Radkovskaya et al. JMMM 2006
Hesmer et al., phys. stat. sol. b 2007

Complex coupling: experiment + theory



Coupling constant (amplitude and phase) vs. distance between the elements for split rings on printed circuit boards

circles: experiment
solid: theory, with retardation
dotted: theory, no retardation

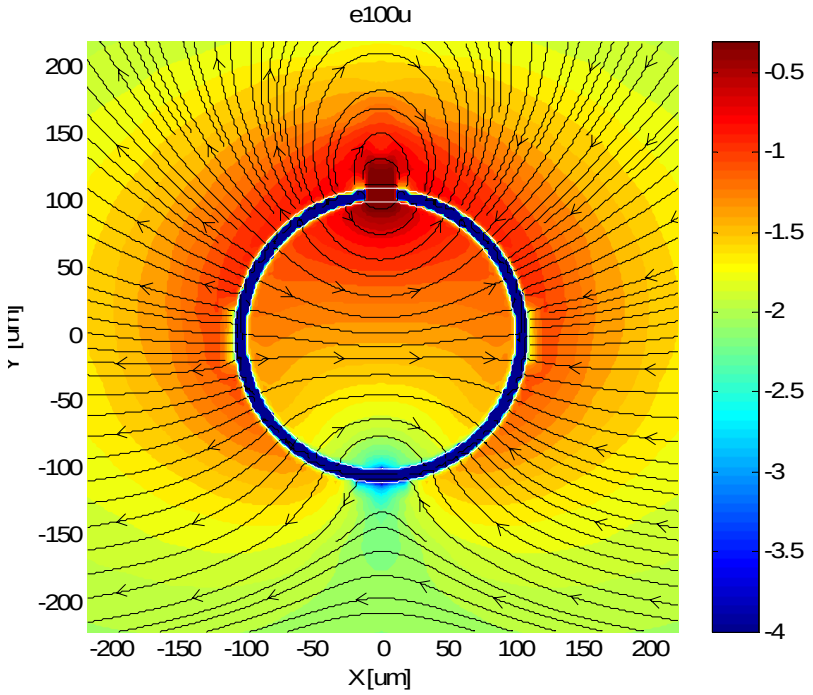
- **coupling constant is complex, declines with distance slowly**
- **theory without retardation clearly fails to describe the experiment**

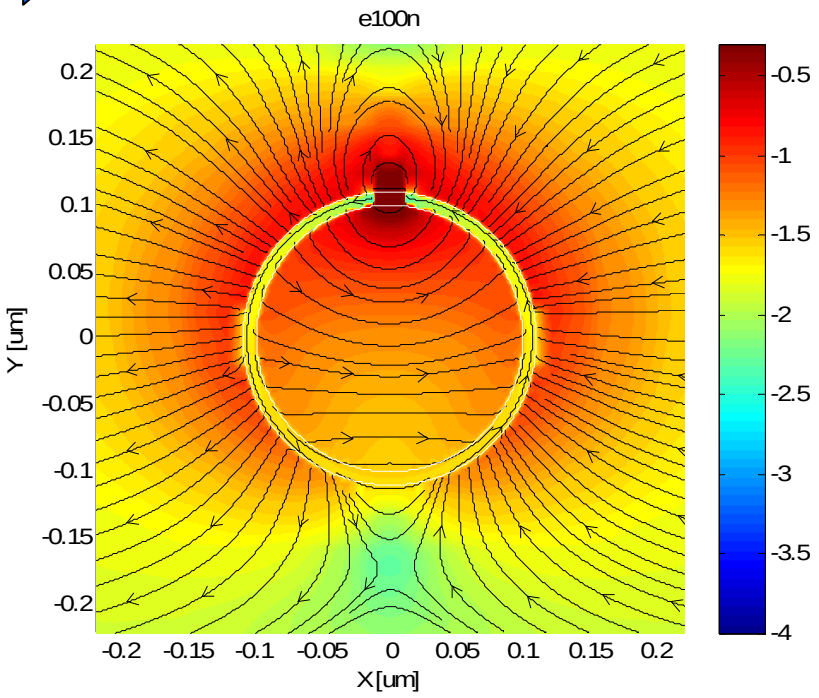
HOW DOES SCALING DOWN TOWARDS OPTICAL FREQUENCIES WORK?

Outlook: Nanostructured metamaterials

HOW DOES SCALING DOWN
TOWARDS OPTICAL FREQUENCIES
WORK?

ring radius 100μm ⟷ ring radius 100nm





Skin effect,
no field inside the metal

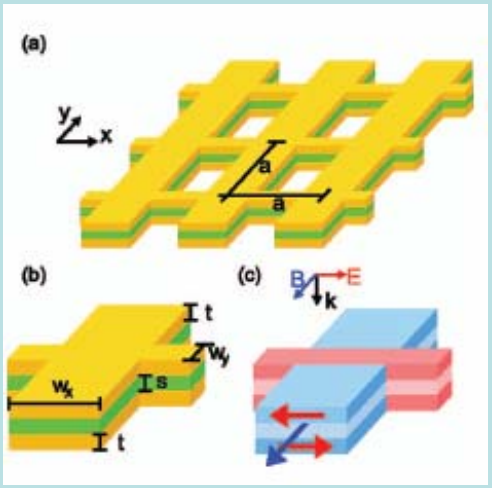
field penetrates the metal,
surface plasmon polaritons

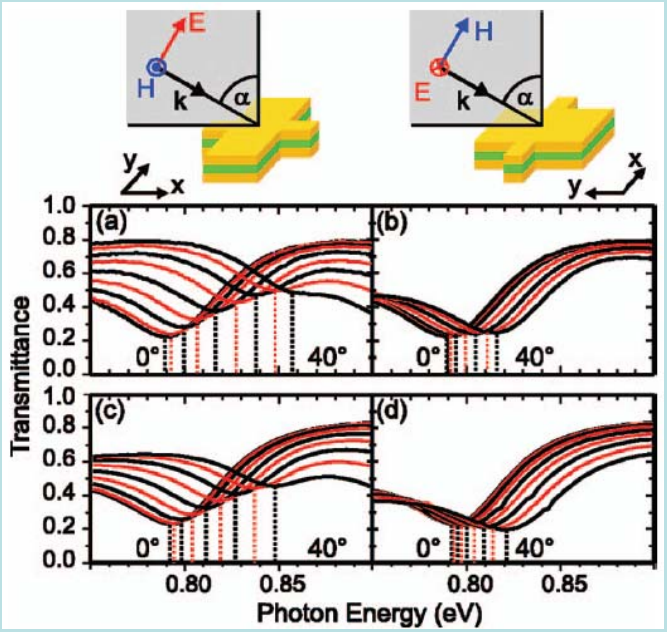
Simulations: CST (Tatartschuk, Erlangen)

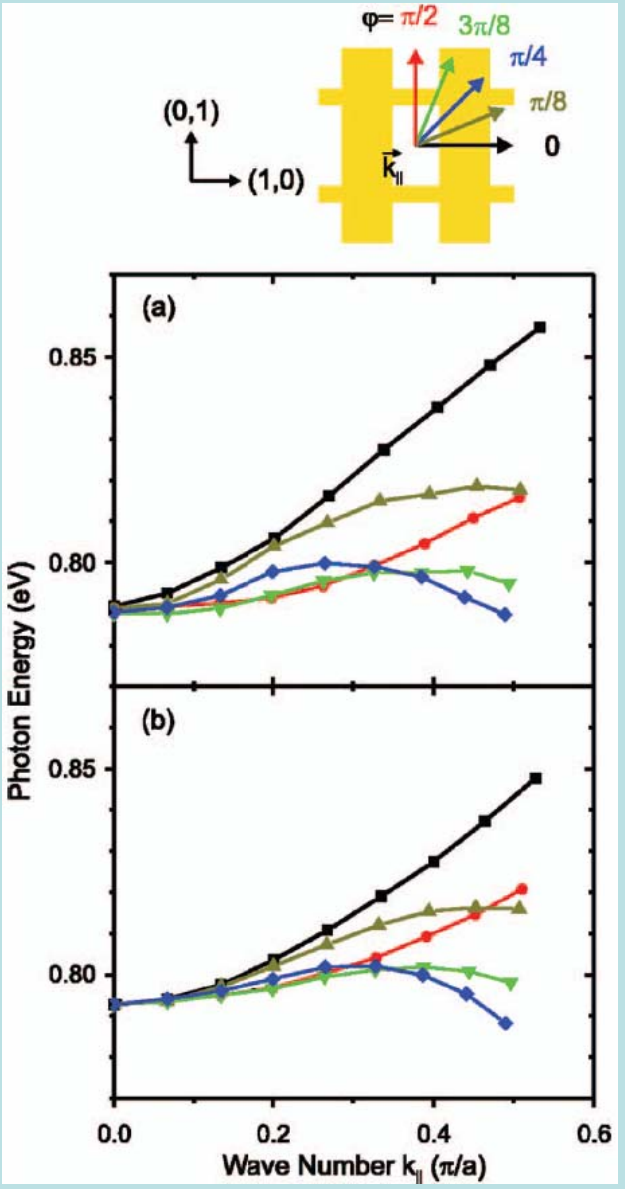
WHAT ABOUT SLOW WAVES OF NEAR FIELD COUPLING AT THZ FREQUENCIES?

Observation of magnetization waves in negative-index photonic metamaterials

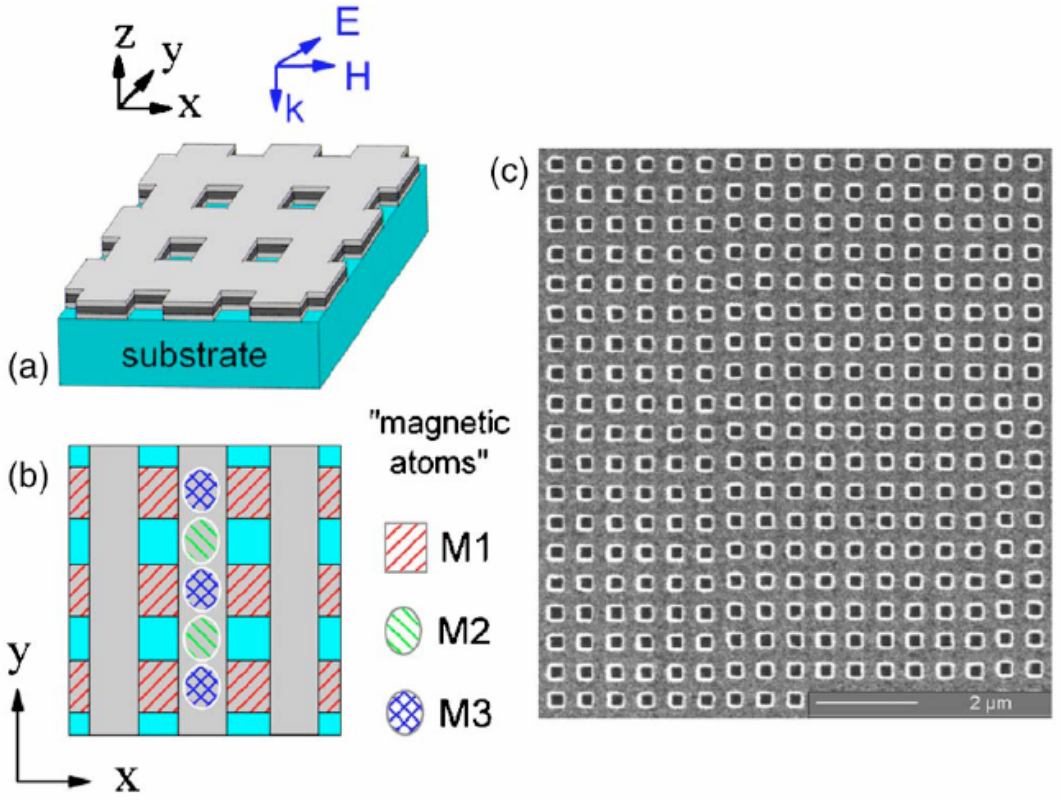
G. Dolling et al., APL (2006)

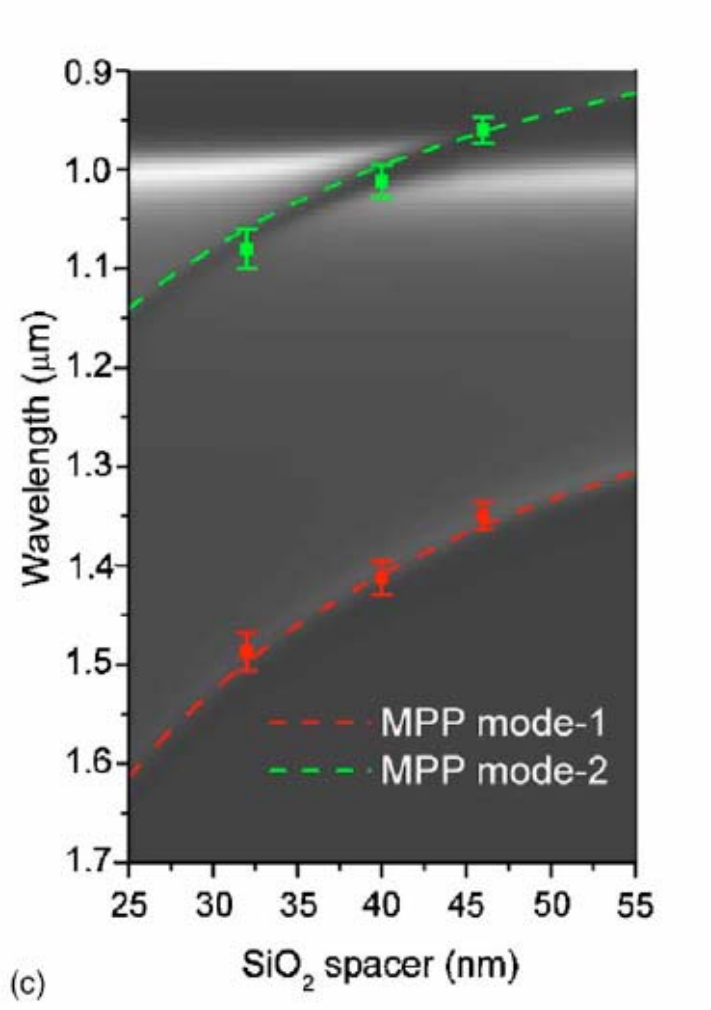






Exploring magnetic plasmon polaritons in optical transmission through hole arrays perforated in trilayer structures





Outlook: Nanostructured metamaterials

- Nanostructuring

- Retardation

- Electric and Magnetic Interactions

- Propagation of slow waves of near field coupling

- Goal: nanostructured near field lens

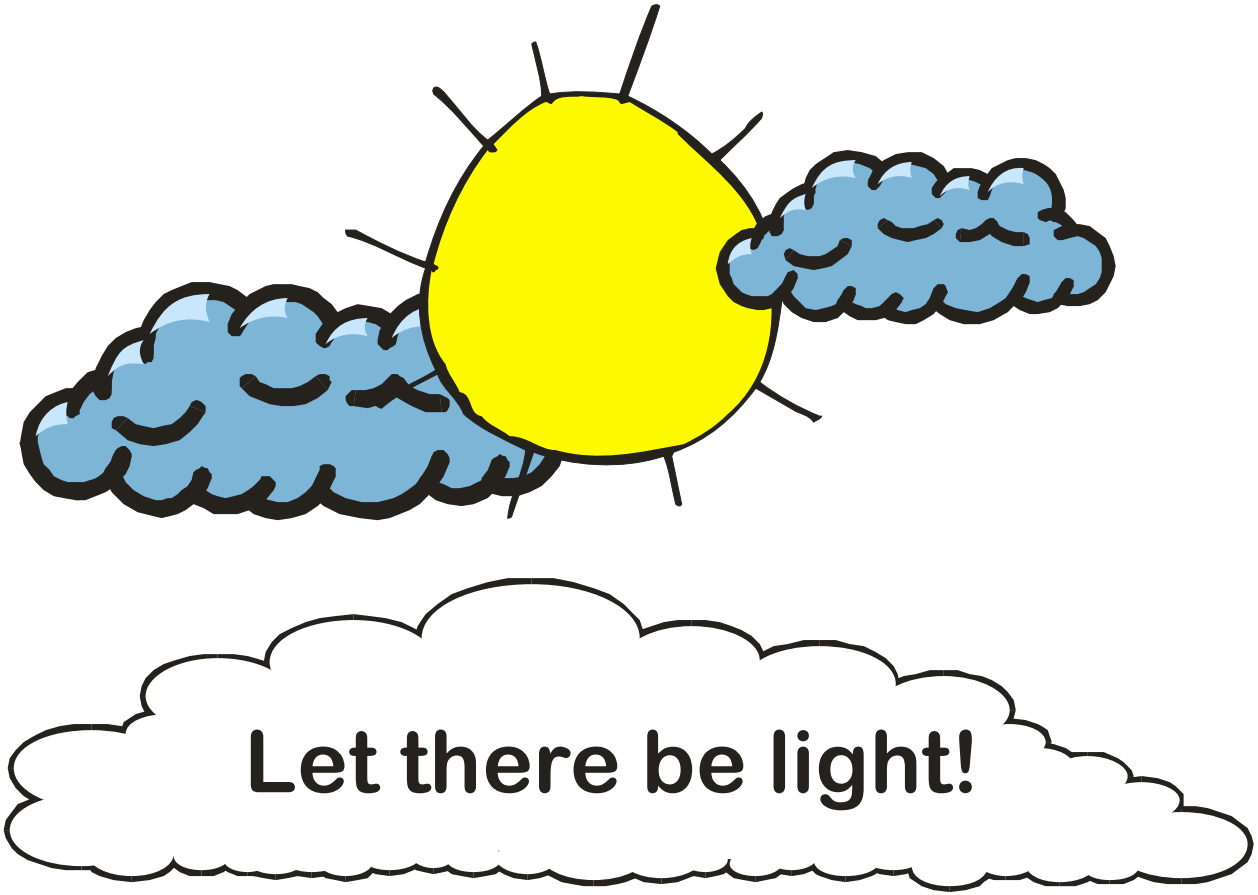
Conclusions

- Slow waves of surface plasmon-polaritons
  - two coupled surfaces in a superlens

- Slow waves of coupling between elements
  - two coupled surfaces in a magnetoinductive lens
  - applications for medical MRI
  - potential applications for nanostructured lenses

Photonics…

Photonics: an old subject…



Women in Photonics?

Women in Photonics!

Conclusions

- Slow waves of surface plasmon-polaritons
  - two coupled surfaces in a superlens
  - flat lens: replication of near field
  - cylindrical lens: magnified image

- Slow waves of coupling between elements
  - two coupled surfaces in a magnetoinductive lens
  - applications for medical MRI
  - potential applications for nanostructured lenses

Thank you