Near Field Imaging in Metamaterials

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
\[ d \ll \lambda \]

Elements must be resonant

- Split Ring Resonator
- Capacitively Loaded Ring
- Swiss Roll

Coupling between elements: magnetoinductive (MI) waves

\[ m-1 \quad m \quad m+1 \]
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

Pendry et al., Science 2004

object

image
Interaction of elements: Magnetoinductive (MI) waves

Kirchhoff's Law:

\[ [R + j\omega L(1 - \frac{\omega_0^2}{\omega^2})]I_m + j\omega M (I_{m-1} + I_{m+1}) = 0 \]

self-impedance

mutual impedance

Wave ansatz:

\[ I_m = I_0e^{j(\omega t - mkd)} \]

coupling constant

Dispersion:

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

Shamonina et al., Electr.Lett. 2002
Shamonina et al., J. Appl. Phys. 2002
Interaction of elements: Magnetoinductive (MI) waves

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

Frequencies $f$ [MHz] vs. propagation constant $kd/\pi$

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

\[ \omega / \omega_0 = 0.98 \]

\[ \omega / \omega_0 = 1.15 \]

Zhuromskyy et al., Optics Express 2005
Swiss Roll Near Field Lens

Zhuromskyy et al., Optics Express 2005
Nearest Field Magnetoinductive Lens

- No sub-λ-imaging around the resonance frequency

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

Freire and Marques, Appl. Phys. Lett. 86, 182505, 2005
Near Field Magnetoinductive Lens

The mechanism?


Experiment: Radkovskaya (Moscow, Oxford)
The resonant elements of the lens: split pipes

\[ r_0 = 10 \text{ mm} \]
\[ w = 1 \text{ mm} \]
\[ g = 1 \text{ mm} \]
\[ l = 5 \text{ mm} \]
\[ f_0 = 46.2 \text{ MHz} \]
\[ Q = 105 \]


Experiment: Radkovskaya (Moscow, Oxford)
Near-field Magnetoinductive Lens

The mechanism?

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

Dispersion relations: theory and experiment

Near-field Magnetoinductive Lens

The mechanism?

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

Dispersion relations: theory and experiment

Experiment: Radkovskaya (Moscow, Oxford)

Near-field MI lens: theory and experiment


Image width vs. frequency

2 layers x 11 split pipes

$h=10\text{mm}$, $r_0=10\text{mm}$, $f_0=46\text{ MHz}$

Theory

Experiment

The narrowest image

$\lambda/300$
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

Swiss Rolls


- radius $r \sim 1$ cm
- frequency $f \sim 20$ MHz
  wavelength $\lambda \sim 15$ 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 $r \sim 1$ cm
- frequency $f \sim 2$ GHz
  wavelength $\lambda \sim 15$ 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
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
Coupling constant (amplitude and phase) vs. distance between the elements for split rings on printed circuit boards

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

circles: experiment
solid: theory, with retardation
dotted: theory, no retardation
Outlook: Nanostructured metamaterials

HOW DOES SCALING DOWN TOWARDS OPTICAL FREQUENCIES WORK?
Outlook: Nanostructured metamaterials

HOW DOES SCALING DOWN TOWARDS OPTICAL FREQUENCIES WORK?

ring radius 100μm

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…

Let there be light!
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