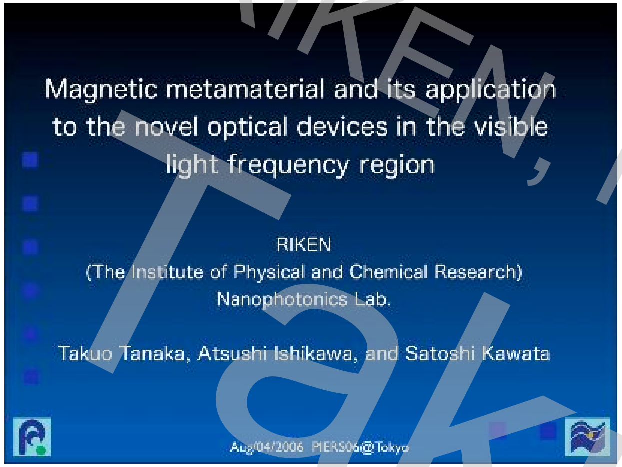
Magnetic metamaterial and its application to the novel optical devices in the visible light frequency region
RIKEN
(The Institute of Physical and Chemical Research)
Nanophotonics Lab.
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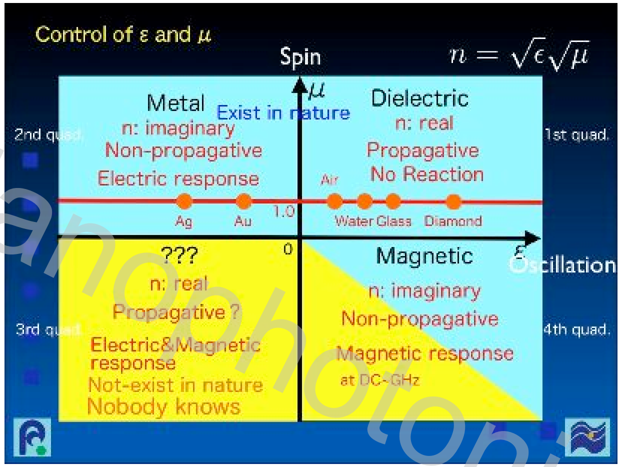
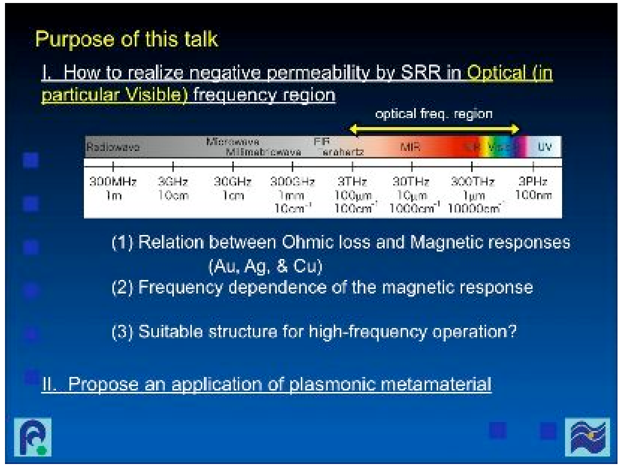
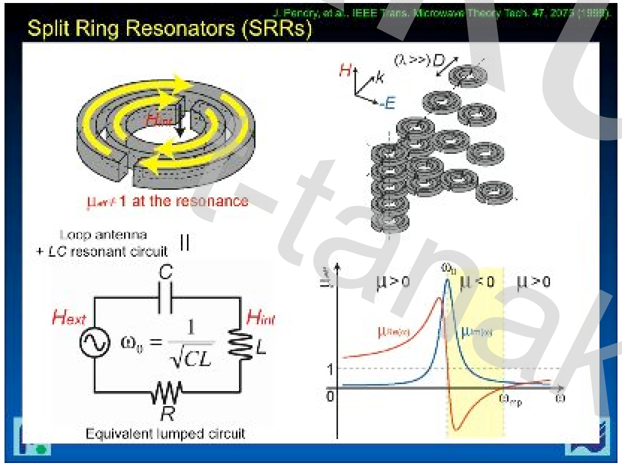
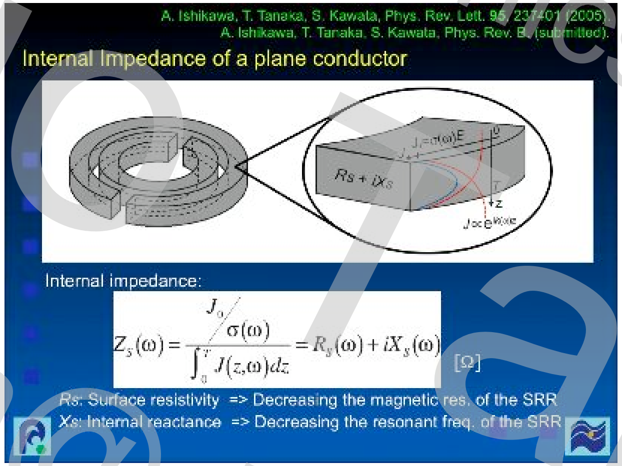
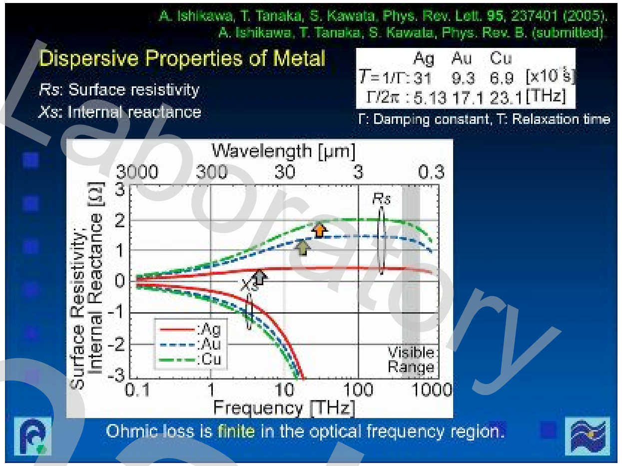
Aug/04/2006 PIERS06@Tokyo

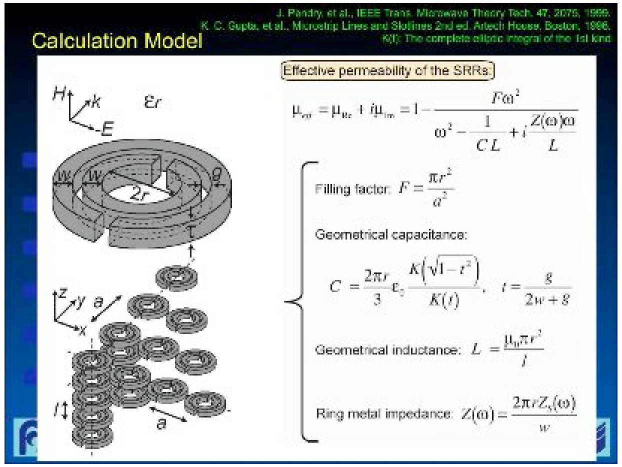

Control of ε and μ
Spin
n = √ε√μ
2nd quad.
1st quad.
3rd quad.
4th quad.
Metal
n: imaginary
Non-propagative
Electric response
Exist in nature
Dielectric
n: real
Propagative
No Reaction
Air
Ag
Au
1.0
Water Glass
Diamond
???
n: real
Propagative ?
Electric&Magnetic response
Not-exist in nature
Nobody knows
Magnetic
n: imaginary
Non-propagative
Magnetic response
at DC-GHz
Oscillation

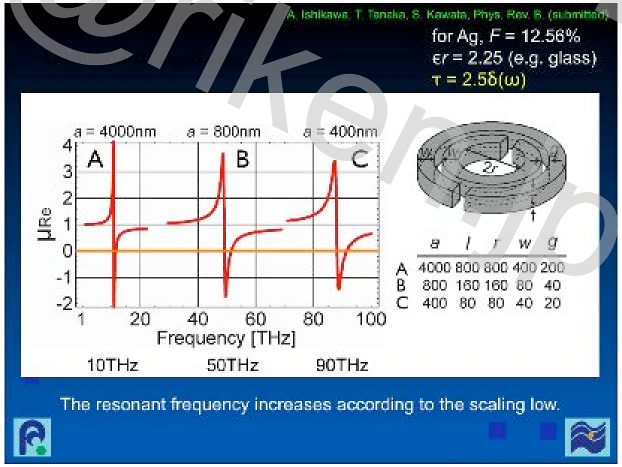

Purpose of this talk
I. How to realize negative permeability by SRR in Optical (in particular Visible) frequency region
optical freq. region
(1) Relation between Ohmic loss and Magnetic responses (Au, Ag, & Cu)
(2) Frequency dependence of the magnetic response
(3) Suitable structure for high-frequency operation?
II. Propose an application of plasmonic metamaterial

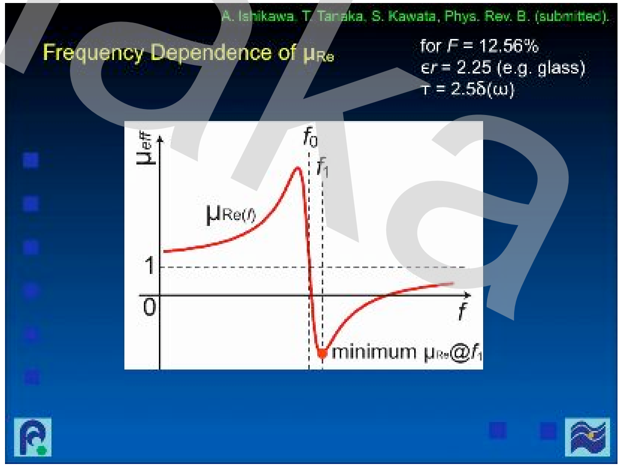

Split Ring Resonators (SRRs)
J. Pendry, et al., IEEE Trans. Microwave Theory Tech. 47, 2075 (1999).
μeff ≠ 1 at the resonance
Loop antenna + LC resonant circuit
Hext
Hint
ω0 = 1/√CL
C
L
R
Equivalent lumped circuit
μ>0
μ<0
μ>0

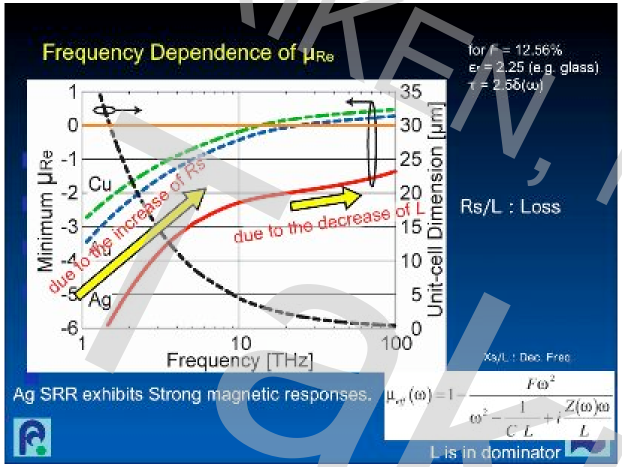

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. B. (submitted).
Internal Impedance of a plane conductor
Rs + iXs
Internal impedance:
Zs(ω) = (J0/σ(ω)) / ∫ J(z,ω)dz = Rs(ω) + iXs(ω) [Ω]
Rs: Surface resistivity => Decreasing the magnetic res. of the SRR
Xs: Internal reactance => Decreasing the resonant freq. of the SRR

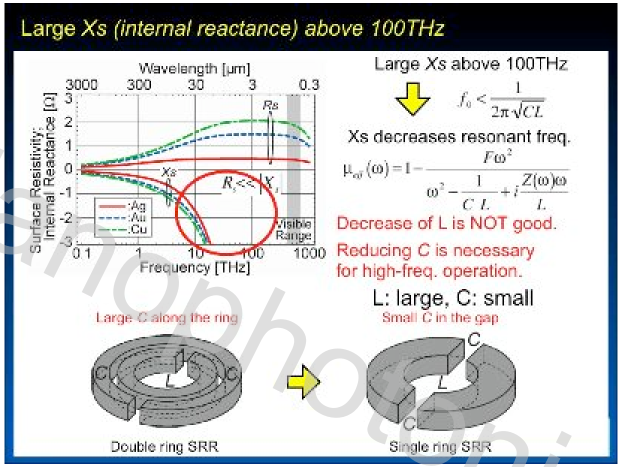

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. B. (submitted).
Dispersive Properties of Metal
Rs: Surface resistivity
Xs: Internal reactance
Ag Au Cu
T=1/Γ: 31 9.3 6.9 [x10⁻¹⁵s]
Γ/2π: 5.13 17.1 23.1 [THz]
Γ: Damping constant, T: Relaxation time
Wavelength [μm]
Surface Resistivity, Internal Reactance [Ω]
Frequency [THz]
Visible Range
Ohmic loss is finite in the optical frequency region.

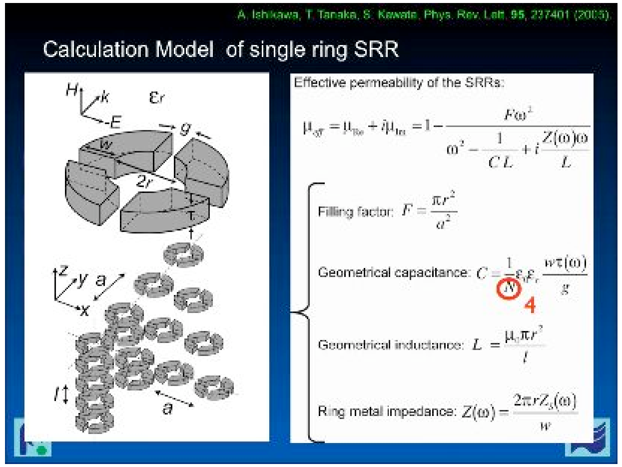

J. Pendry, et al., IEEE Trans. Microwave Theory Tech. 47, 2075, 1999.
K. C. Gupta, et al., Microstrip Lines and Slotlines 2nd ed. Artech House, Boston, 1996.
K(t): The complete elliptic integral of the 1st kind
Calculation Model
Effective permeability of the SRRs:
μeff = μRe + iμIm = 1 − Fω² / (ω² − 1/(CL) + i Z(ω)ω/L)
Filling factor: F = πr²/a²
Geometrical capacitance:
C = (2πr/3) ε0 K(√(1−t²))/K(t), t = g/(2w+g)
Geometrical inductance: L = μ0πr²/l
Ring metal impedance: Z(ω) = 2πrZs(ω)/w

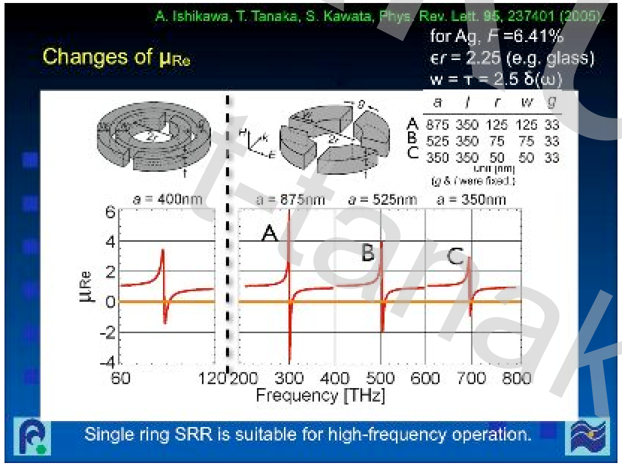

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. B. (submitted).
for Ag, F = 12.56%
εr = 2.25 (e.g. glass)
τ = 2.5δ(ω)
a = 4000nm
a = 800nm
a = 400nm
μRe
Frequency [THz]
10THz
50THz
90THz
a l r w g
A 4000 800 800 400 200
B 800 160 160 80 40
C 400 80 80 40 20
The resonant frequency increases according to the scaling low.

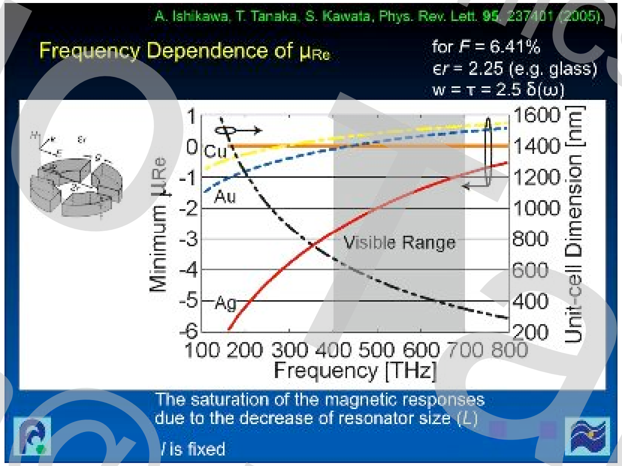

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. B. (submitted).
Frequency Dependence of μRe
for F = 12.56%
εr = 2.25 (e.g. glass)
τ = 2.5δ(ω)
μeff
μRe(f)
minimum μRe@f1

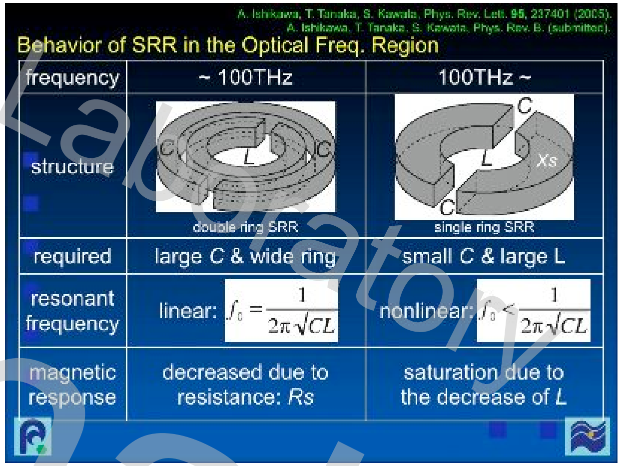

Frequency Dependence of μRe
for F = 12.56%
εr = 2.25 (e.g. glass)
τ = 2.5δ(ω)
Minimum μRe
Cu
Au
Ag
due to the increase of Rs
due to the decrease of L
Unit-cell Dimension [μm]
Frequency [THz]
Rs/L : Loss
Xs/L : Dec. Freq.
Ag SRR exhibits Strong magnetic responses.
L is in dominator


Large Xs (internal reactance) above 100THz
Wavelength [μm]
Surface Resistivity: Internal Reactance [Ω]
Frequency [THz]
Visible Range
Large Xs above 100THz
Xs decreases resonant freq.
Decrease of L is NOT good.
Reducing C is necessary for high-freq. operation.
L: large, C: small
Large C along the ring
Small C in the gap
Double ring SRR
Single ring SRR

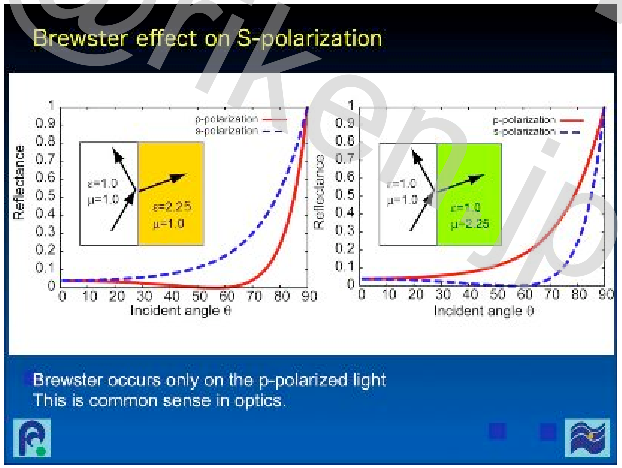

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
Calculation Model of single ring SRR
Effective permeability of the SRRs:
Filling factor:
Geometrical capacitance:
Geometrical inductance:
Ring metal impedance:

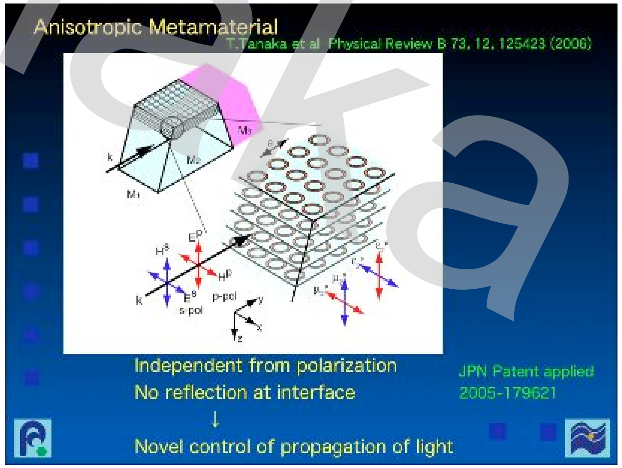

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
Changes of μRe
for Ag, F =6.41%
εr = 2.25 (e.g. glass)
w = τ = 2.5 δ(ω)
a = 400nm
a = 875nm
a = 525nm
a = 350nm
Frequency [THz]
Single ring SRR is suitable for high-frequency operation.


A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
Frequency Dependence of μRe
for F = 6.41%
εr = 2.25 (e.g. glass)
w = τ = 2.5 δ(ω)
Minimum μRe
Visible Range
Unit-cell Dimension [nm]
Frequency [THz]
The saturation of the magnetic responses
due to the decrease of resonator size (L)
l is fixed

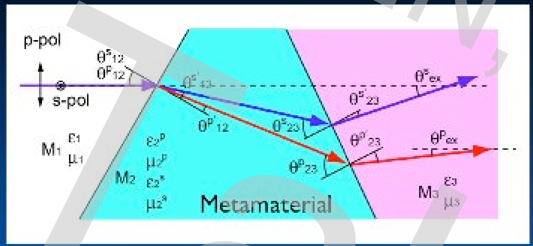

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. B. (submitted).
Behavior of SRR in the Optical Freq. Region
frequency
~ 100THz
100THz ~
structure
double ring SRR
single ring SRR
required
large C & wide ring
small C & large L
resonant frequency
linear:
nonlinear:
magnetic response
decreased due to resistance: Rs
saturation due to the decrease of L

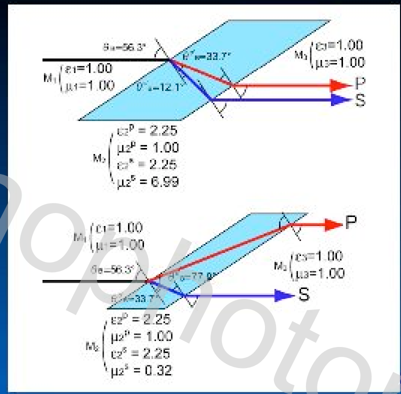

An application of the metamaterial


Brewster effect on S-polarization
Reflectance
Incident angle θ
p-polarization
s-polarization
Brewster occurs only on the p-polarized light
This is common sense in optics.

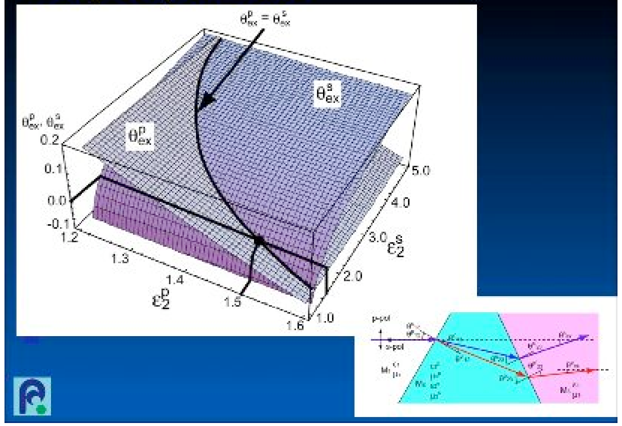

Anisotropic Metamaterial
T.Tanaka et al. Physical Review B 73, 12, 125423 (2006)
Independent from polarization
No reflection at interface
↓
Novel control of propagation of light
JPN Patent applied
2005-179621

Calculation method

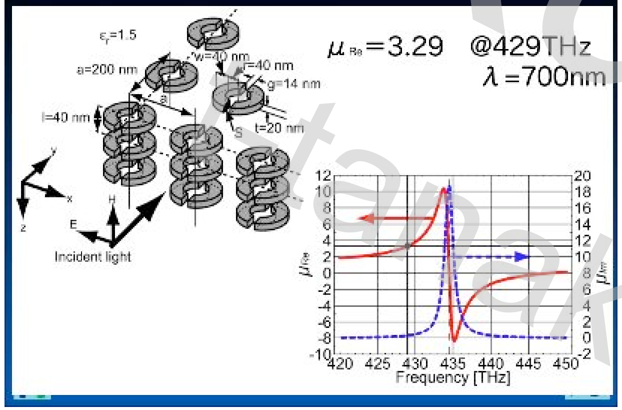




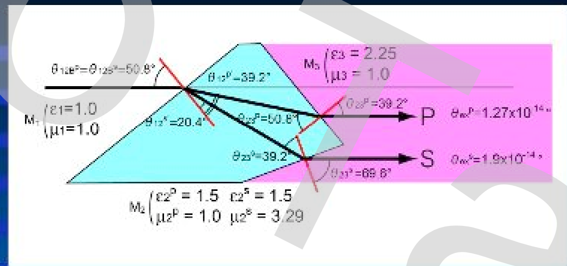
Seeking ε and μ combination



Design of nano-sized resonator



Unpolarized Brewster window



Details will be presented in PIERS 2006 @Tokyo

Conclusion

- Magnetic permeability of split ring resonator is investigated from THz to the visible light region.
- (1) ~ 100THz, strong effect of *Rs (surface resistivity)*
  => Decrease of magnetic response due to the Ohmic loss

  (2) 100THz ~, strong effect of *Xs(internal reactance)*
  => Reducing C is necessary for high-frequency operation.
  => Saturation of magnetic response in the visible range
  => Limitation of the operating frequency of the SRR
- Ag & 3D SRR array exhibits the negative μ in the visible region.
  We ignored the problem of oxidization or sulfuration of Ag.