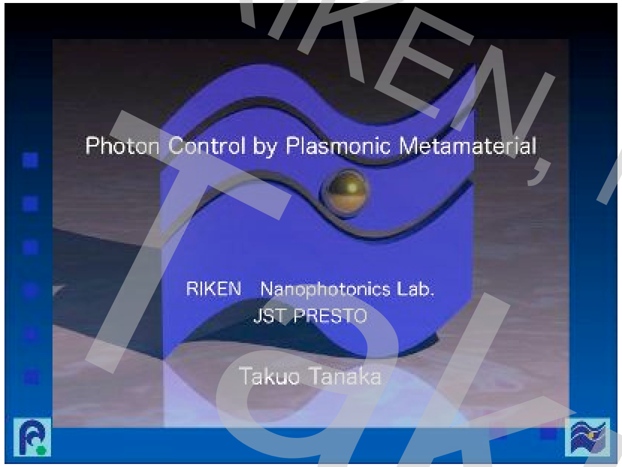


Photon Control by Plasmonic Metamaterial

RIKEN Nanophotonics Lab.
JST PRESTO

Takuo Tanaka

Outline

1. Plasmonic metamaterial
2. Design of metamaterial
3. Application of metamaterial for controling photons
4. (Fabrication techniques) -> Poster session

Maxwell equations

-> Describe propagation of light

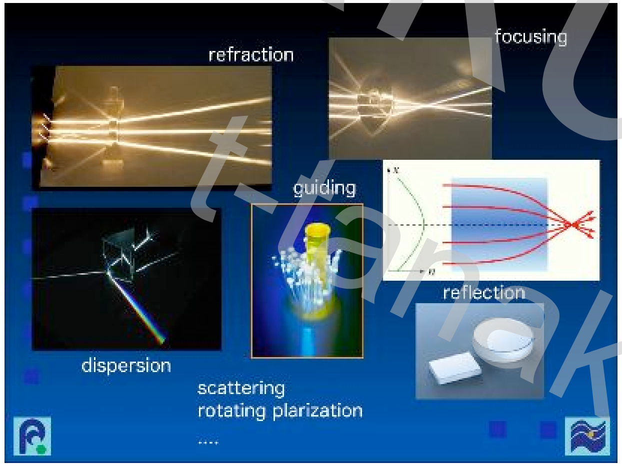
$$rot\mathbf{E} = -\mu\frac{\partial \mathbf{H}}{\partial t}$$

$$div\mathbf{D} = \rho$$

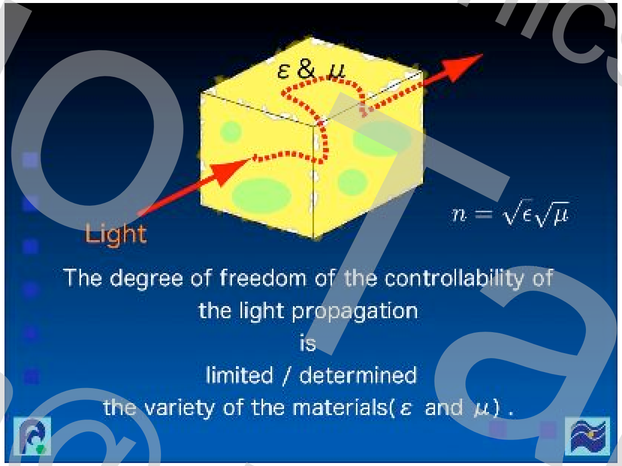
$$rot\mathbf{H} = \mathbf{j} + \epsilon\frac{\partial \mathbf{E}}{\partial t}$$

$$div\mathbf{B} = 0$$

Distribution of ε, μ -> Way of propagation is determined

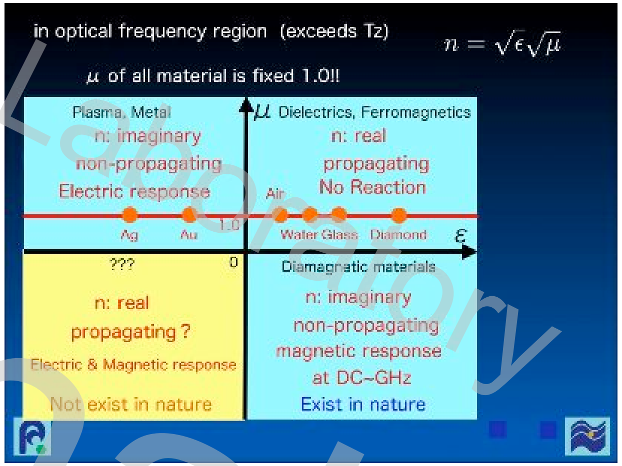


scattering
rotating plarization
....



$n = \sqrt{\epsilon}\sqrt{\mu}$

The degree of freedom of the controllability of the light propagation
is
limited / determined
the variety of the materials(ε and μ) .



in optical frequency region (exceeds Tz)

$n = \sqrt{\epsilon}\sqrt{\mu}$

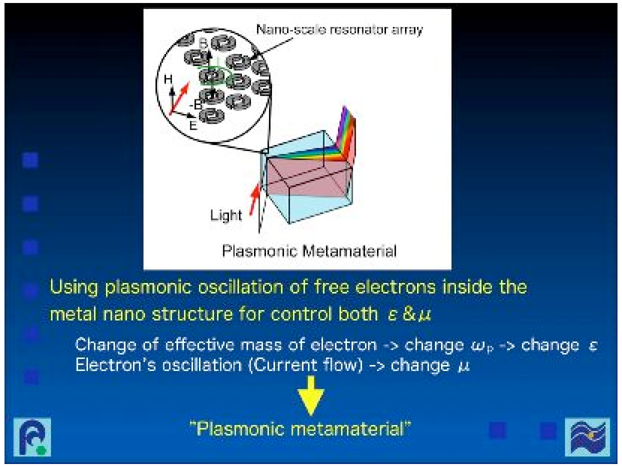
μ of all material is fixed 1.0!!

Plasma, Metal
n: imaginary
non-propagating
Electric response

μ Dielectrics, Ferromagnetics
n: real
propagating
No Reaction

???
n: real
propagating ?
Electric & Magnetic response
Not exist in nature

Diamagnetic materials
n: imaginary
non-propagating
magnetic response
at DC~GHz
Exist in nature

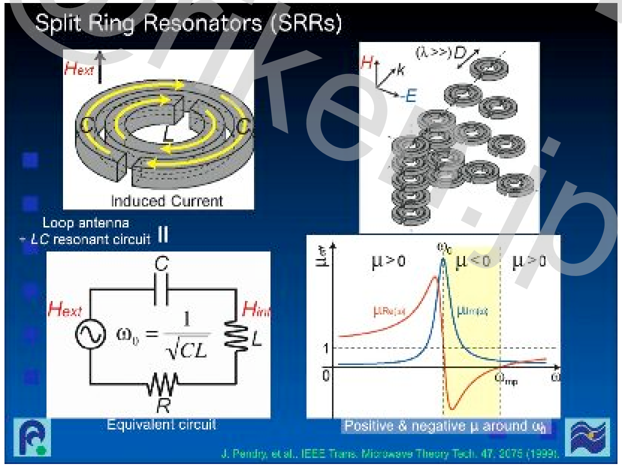


Using plasmonic oscillation of free electrons inside the metal nano structure for control both ε & μ

Change of effective mass of electron -> change ω_p -> change ε
Electron's oscillation (Current flow) -> change μ

"Plasmonic metamaterial"

Split Ring Resonators (SRRs)



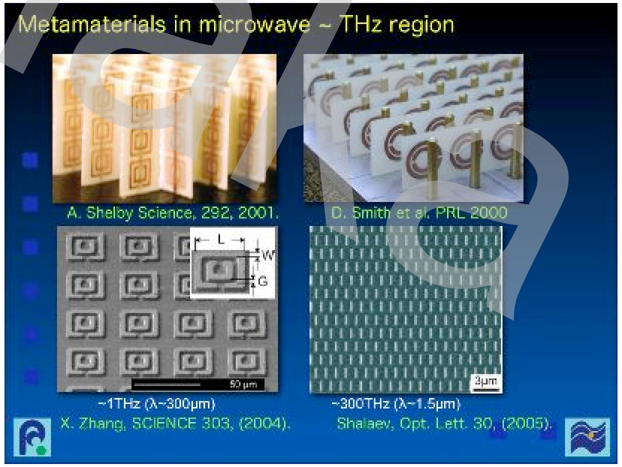
Loop antenna
= LC resonant circuit ||

Equivalent circuit

Positive & negative μ around ω_0

J. Pendry, et al., IEEE Trans. Microwave Theory Tech. 47, 2075 (1999).

Metamaterials in microwave ~ THz region



A. Shelby Science, 292, 2001.

D. Smith et al. PRL 2000

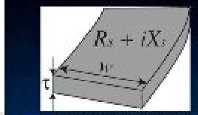
~1THz (λ~300μm)
X. Zhang, SCIENCE 303, (2004).

~300THz (λ~1.5μm)
Shalaev, Opt. Lett. 30, (2005).

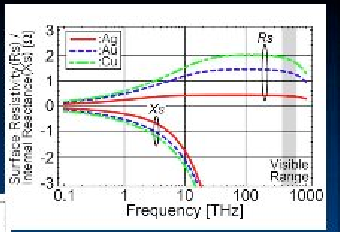
Can we make metamaterials in optical frequency region?

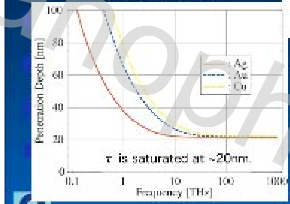
↓

design strategy of metamaterials



Rs:surface resistance
Xs:internal reactance
τ :penetration depth
w :width of the ring





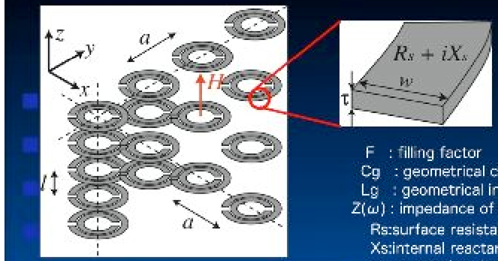
τ is saturated at ~20nm.

Rs is saturated in the frequency region above 100THz.

Xs increases according to the frequency.

Silver is ideal for the SRRs' material.

A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. **95**, 237401 (2005).

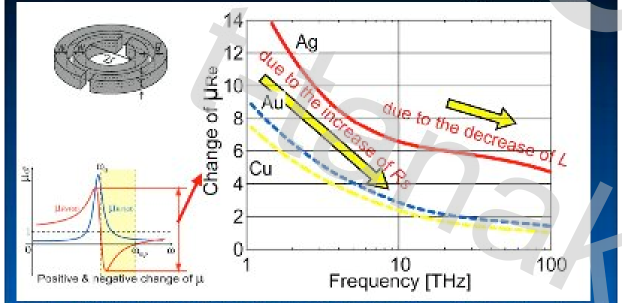


$$\mu_{eff}(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \frac{1}{C_g L_g} + i\frac{Z(\omega)\omega}{L_g}}$$

F : filling factor
Cg : geometrical capacitance
Lg : geometrical inductance
Z(ω) : impedance of the circuit
Rs:surface resistance
Xs:internal reactance
τ :penetration depth
w :width of the ring

Frequency Dependence of μ_{Re}

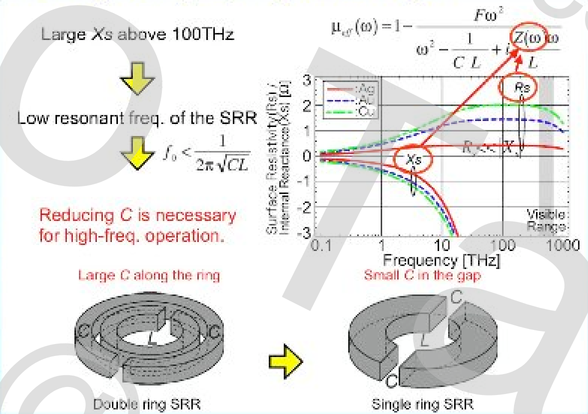
$$\mu_{eff}(\omega) = 1 - \frac{F\omega^2}{\omega^2 - \frac{1}{C L} + i\frac{Z(\omega)\omega}{L}}$$



Ag SRR exhibits Strong magnetic responses.

Rs/L : Loss
Xs/L : Dec. Freq.

Increasing working frequency to visible region



Large Xs above 100THz

Low resonant freq. of the SRR

$$f_0 < \frac{1}{2\pi\sqrt{CL}}$$

Reducing C is necessary for high-freq. operation.

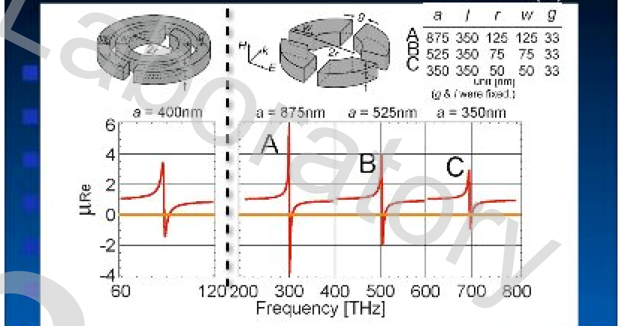
Large C along the ring

Small C in the gap

Double ring SRR

Single ring SRR

Phys. Rev. Lett. **95**, 237401 (2005).
for Ag, F =6.41%
εr = 2.25 (e.g. glass)
w = τ = 2.5 δ(ω)

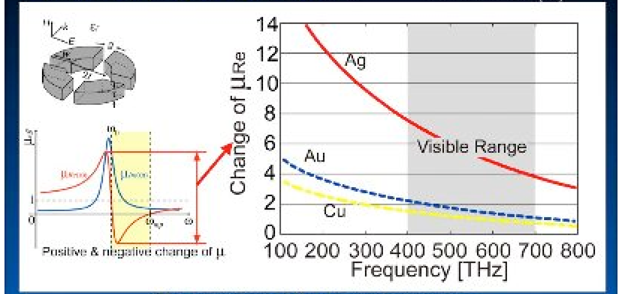


	a	l	r	w	g
A	875	350	125	125	33
B	525	350	75	75	33
C	350	350	50	50	33

unit [nm]
(g & l were fixed.)

Phys. Rev. Lett. **95**, 237401 (2005).
for F = 6.41%
εr = 2.25 (e.g. glass)
w = τ = 2.5 δ(ω)

frequency dependence of μ_{Re}

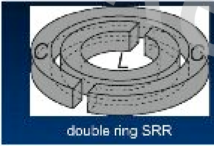
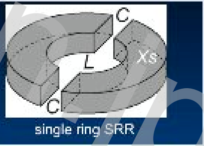


The saturation of the magnetic responses due to the decrease of resonator size (L)

l is fixed

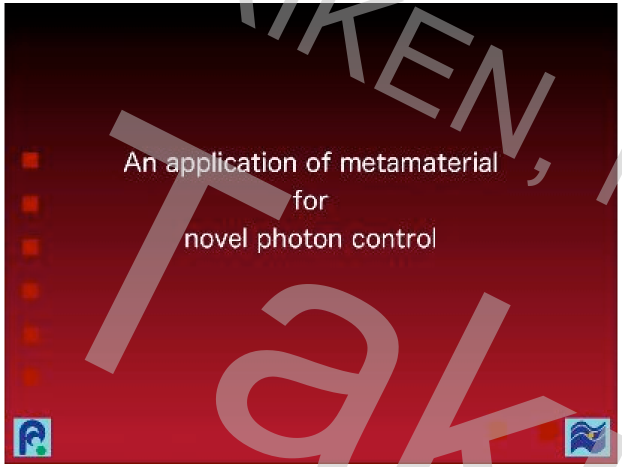
Phys. Rev. Lett. **95**, 237401 (2005).
J. Opt. Soc. Am. B (accepted for publication)

Design strategy of nano-resonator

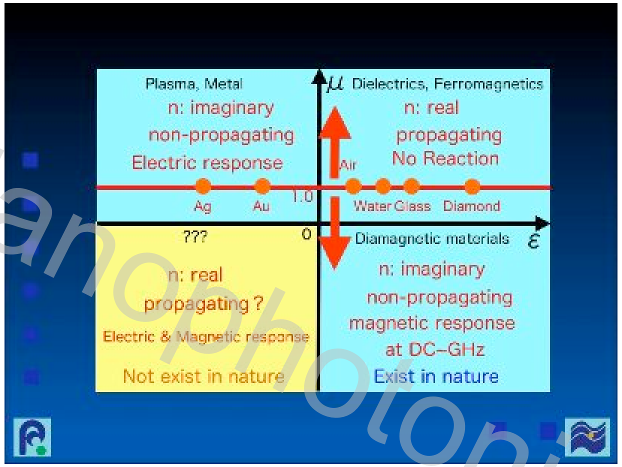
frequency	~ 100THz	100THz ~
structure	 double ring SRR	 single ring SRR
required	large C & wide ring	small C & large L
resonant frequency	linear: $f_0 = \frac{1}{2\pi\sqrt{CL}}$	nonlinear: $f_0 < \frac{1}{2\pi\sqrt{CL}}$
magnetic response	decreased due to resistance: Rs	saturation due to the decrease of L

Requirements for realizing metamaterial

1. plasmonic material
   low resistivity (good conductor) -> metal
2. resonator with high Q-value
   shape shoud be well designed
   resonant frequency -> C, L
3. Array
   Three-dimensional array structure



An application of metamaterial
for
novel photon control



Plasma, Metal
n: imaginary
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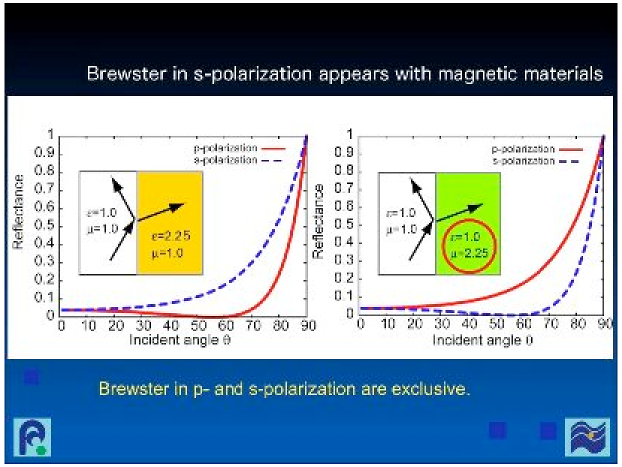
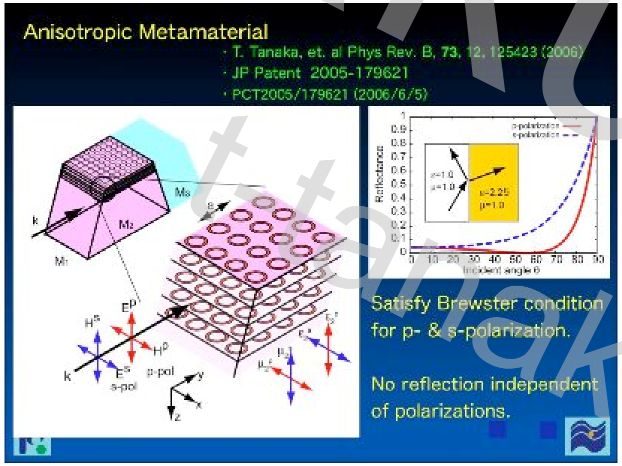


Brewster in s-polarization appears with magnetic materials

Brewster in p- and s-polarization are exclusive.

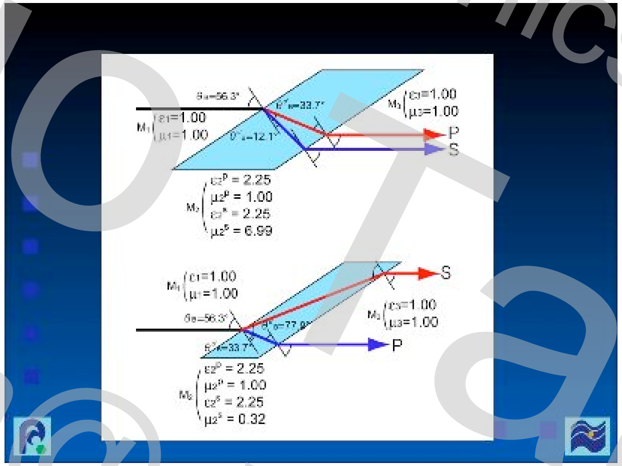


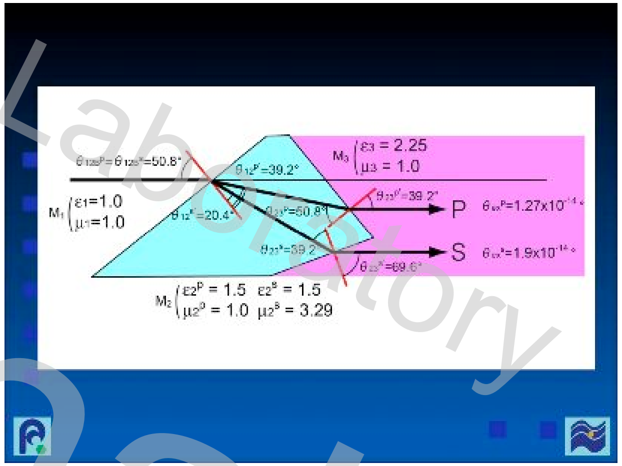
Anisotropic Metamaterial

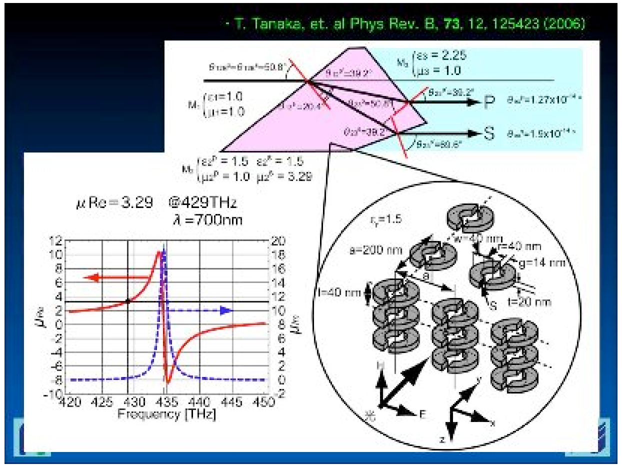
- T. Tanaka, et. al Phys Rev. B, **73**, 12, 125423 (2006)
- JP Patent 2005-179621
- PCT2005/179621 (2006/6/5)

Satisfy Brewster condition for p- & s-polarization.

No reflection independent of polarizations.

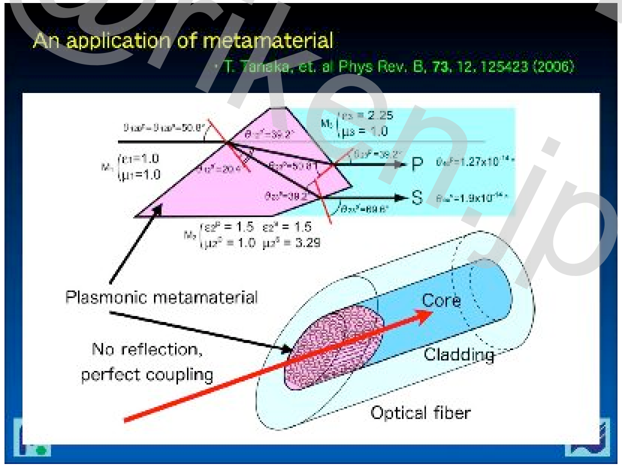






- T. Tanaka, et. al Phys Rev. B, **73**, 12, 125423 (2006)

μRe=3.29 @429THz
λ=700nm

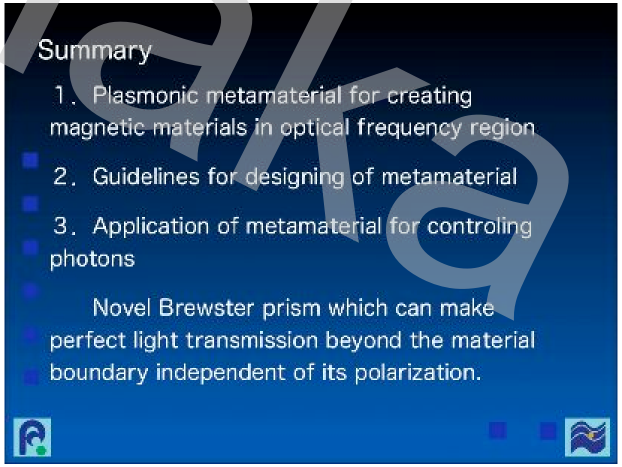


An application of metamaterial

- T. Tanaka, et. al Phys Rev. B, **73**, 12, 125423 (2006)

Plasmonic metamaterial

No reflection,
perfect coupling



Summary

1. Plasmonic metamaterial for creating magnetic materials in optical frequency region
2. Guidelines for designing of metamaterial
3. Application of metamaterial for controling photons

Novel Brewster prism which can make perfect light transmission beyond the material boundary independent of its polarization.

In the poster session

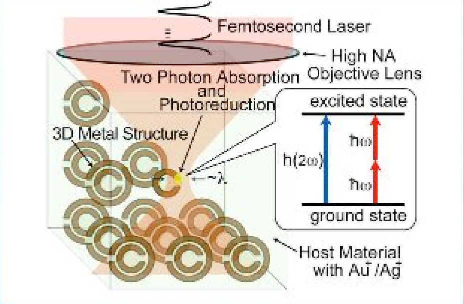
Fabrication techniques

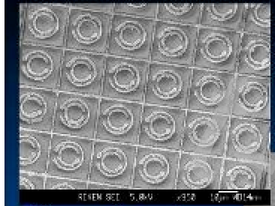
Requirements for realizing metamaterial

1. plasmonic material
   low resistivity (good conductor) -> metal
2. resonator with high Q-value
   shape shoud be well designed
   resonant frequency -> C, L
3. Array
   Three-dimensional array structure

- T. Tanaka et. al. Appl. Phys. Lett. 88, 81107 (2006).
- JPN Patent Applied 2003-175819, 2005-96327
- USPatent 10/808,517

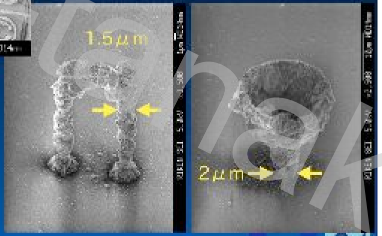
Direct drawing metal structure





Low resistivity metal structure.

Response at around λ=100μm

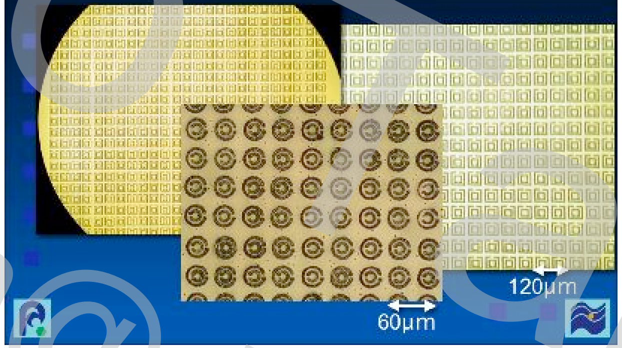


JPN Patent Applied
2004-320101
2005-6188
2005-6038
2005-139329
etc.

Two-photon reduction of complex metal ions

Au^{3+} doped PMMA
（λ=800nm, two-photon reduction, Stage-scan）

Direct drawing of Au wires of 1μm in width.



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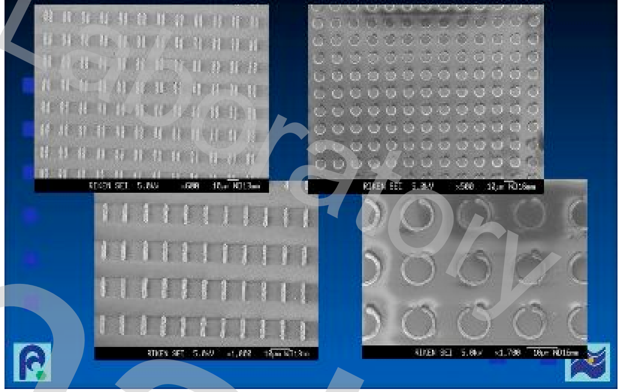
control ε　　control μ



3D polymer structure + metal coating