Magnetic assambly of three-dimensional metamaterials

RIKEN Metamaterials Lab.
Hokkaido University Joint Lab.

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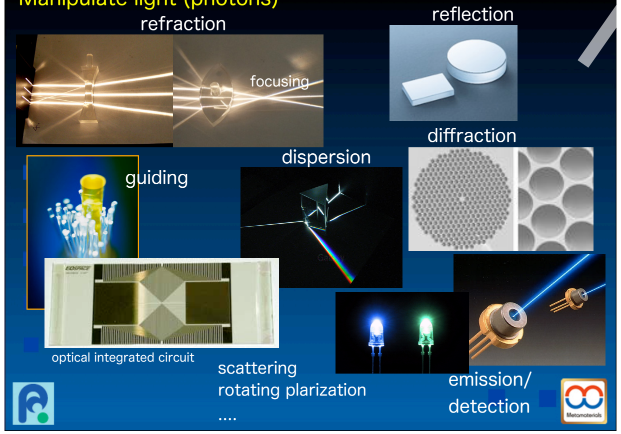
14:00-14:25 June 22, 2011 MORIS2011@Nijmegen, Netherlands

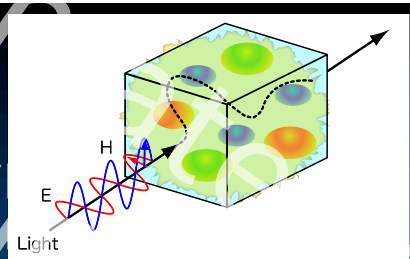
Outline

1. Plasmonic Metamaterials - Background
2. Structures of plasmonic metamaterials that works in visible light region
3. Fabrication techniques for 3D metamaterials
   - Magnetic assembly of 3D metamaterials
   - ((Two-photon-induced metal ion reduction))

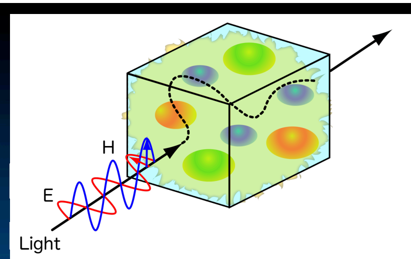
Manipulate light (photons)

Manipulate light (photons)



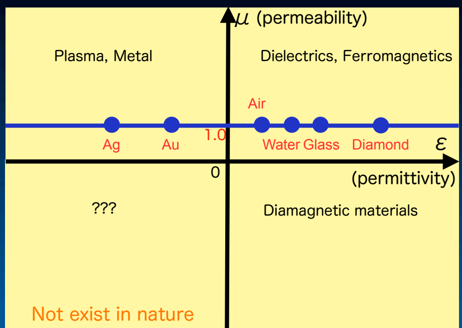


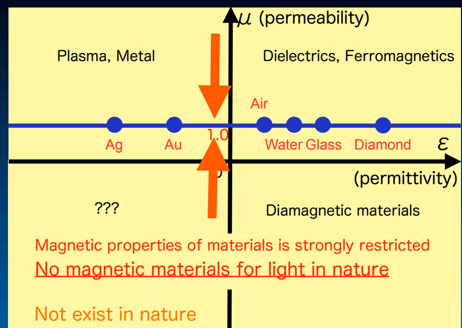
History of optics/photonics is the history of design and fabrication of index distributions.



The degree of freedom of the controllability of the light (propagation) is limited/determined by the variety of refractive indices of materials.

In optical frequency region, all materials are only on the one line (μ=1.0).





refractive index

$$n = \sqrt{\epsilon}\sqrt{\mu}$$ <in electromagnetics>

permittivity permeability

in the light region

μ=1.0, then n is approximated as

$$n = \sqrt{\epsilon}$$ <in optics>

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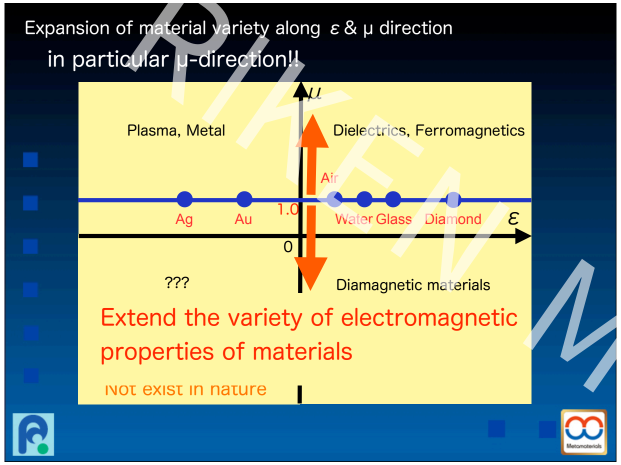
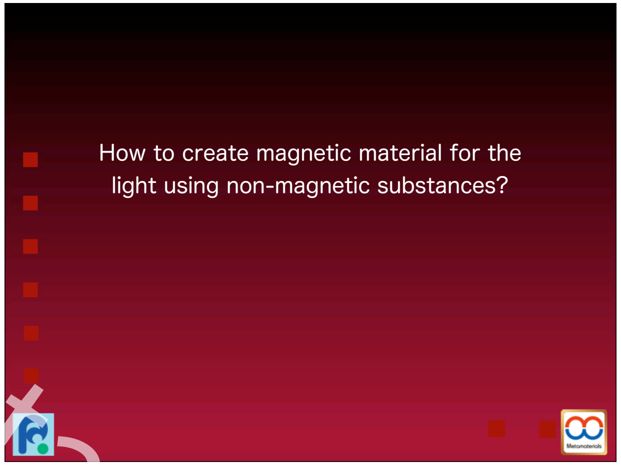
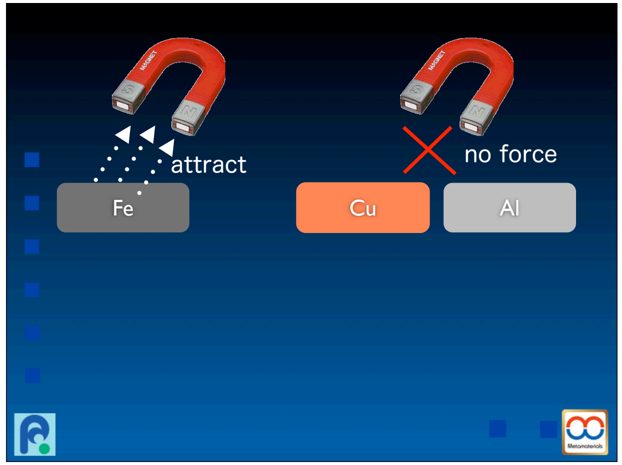


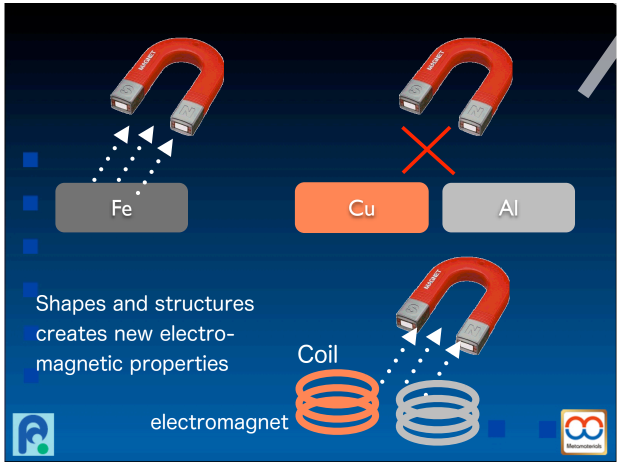
Expansion of material variety along ε & μ direction
in particular μ-direction!!
μ
Plasma, Metal
Dielectrics, Ferromagnetics
Air
Ag
Au
1.0
Water Glass
Diamond
ε
0
???
Diamagnetic materials
Extend the variety of electromagnetic properties of materials
Not exist in nature



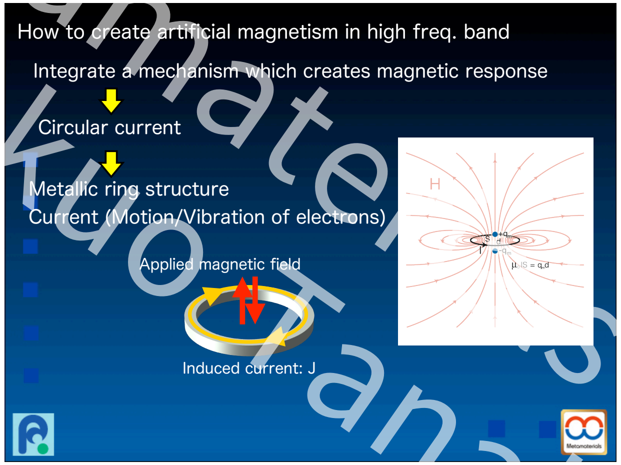
How to create magnetic material for the light using non-magnetic substances?



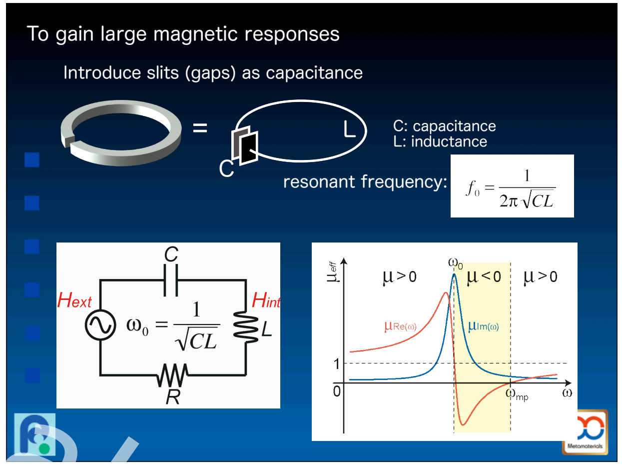
attract
no force
Fe
Cu
Al



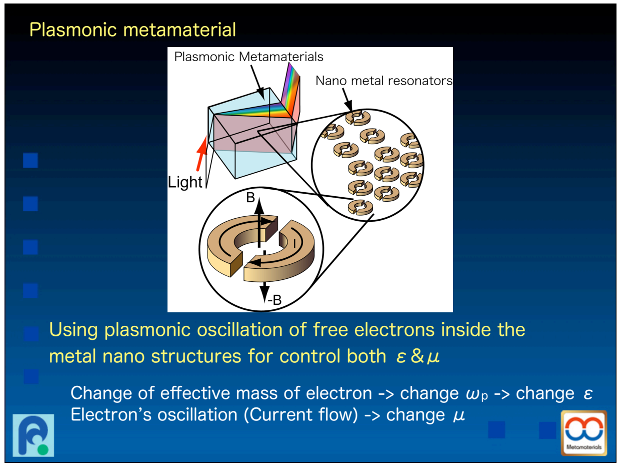
Fe
Cu
Al
Shapes and structures creates new electro-magnetic properties
Coil
electromagnet



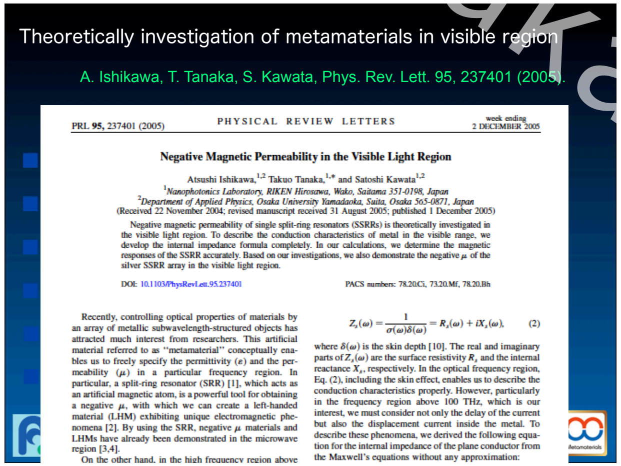
How to create artificial magnetism in high freq. band
Integrate a mechanism which creates magnetic response
Circular current
Metallic ring structure
Current (Motion/Vibration of electrons)
Applied magnetic field
Induced current: J
H



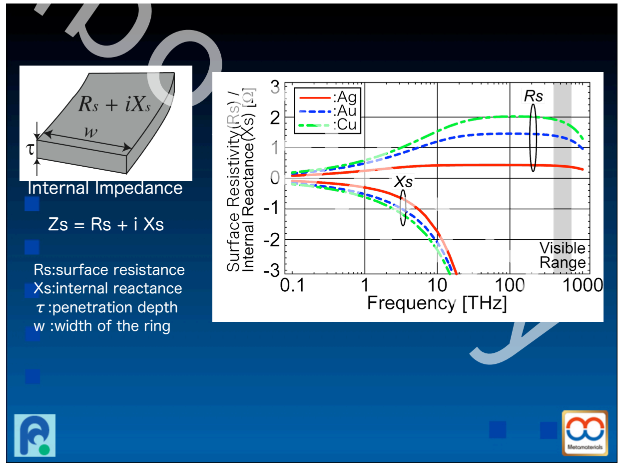
To gain large magnetic responses
Introduce slits (gaps) as capacitance
=
L
C
C: capacitance
L: inductance
resonant frequency:
$f_0 = \frac{1}{2\pi\sqrt{CL}}$
C
Hext
Hint
$\omega_0 = \frac{1}{\sqrt{CL}}$
L
R
μ > 0
μ < 0
μ > 0
ω0
1
0
ω



Plasmonic metamaterial
Plasmonic Metamaterials
Nano metal resonators
Light
B
-B
Using plasmonic oscillation of free electrons inside the metal nano structures for control both ε & μ
Change of effective mass of electron -> change ωp -> change ε
Electron's oscillation (Current flow) -> change μ

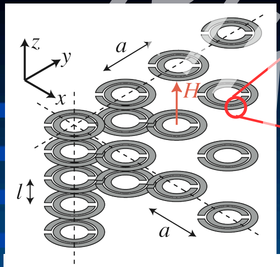


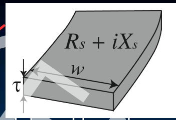
Theoretically investigation of metamaterials in visible region
A. Ishikawa, T. Tanaka, S. Kawata, Phys. Rev. Lett. 95, 237401 (2005).
PRL 95, 237401 (2005)
PHYSICAL REVIEW LETTERS
week ending 2 DECEMBER 2005
Negative Magnetic Permeability in the Visible Light Region
Atsushi Ishikawa, Takuo Tanaka, and Satoshi Kawata



Rs + iXs
w
τ
Internal Impedance
Zs = Rs + i Xs
Rs:surface resistance
Xs:internal reactance
τ :penetration depth
w :width of the ring
Ag
Au
Cu
Rs
Xs
Surface Resistivity(Rs) / Internal Reactance(Xs) [Ω]
Visible Range
Frequency [THz]
0.1
1
10
100
1000

A. Ishikawa, T. Tanaka, S. Kawata, PRL **95**, 237401 (2005).





Internal Impedance

Zs = Rs + i Xs

Rs:surface resistance

Xs:internal reactance

τ :penetration depth

w :width of the ring

Properties of metals

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

F : filling factor

Cg : geometrical capacitance

Lg : geometrical inductance

Z(ω) : impedance of the circuit

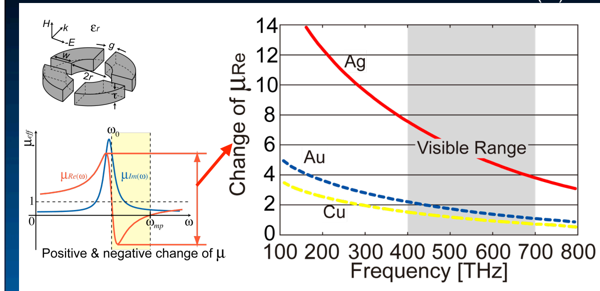
Phys. Rev. Lett. **95**, 237401 (2005).

for F = 6.41%

εr = 2.25 (e.g. glass)

w = τ = 2.5 δ(ω)

frequency dependence of μ_{Re}

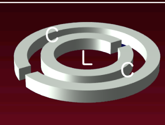
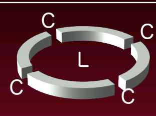


The saturation of the magnetic responses due to the decrease of resonator size (L)

l is fixed

J. Opt. Soc. Am. B, **24**, 510 (2007).

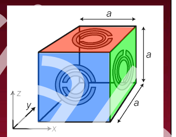
Design strategy of nano-resonator

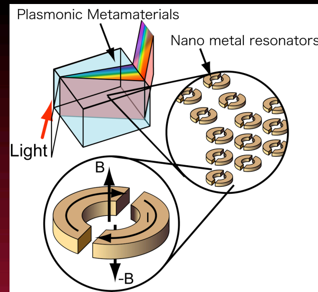
frequency	~ 100THz	100THz ~
structure	 double ring SRR	 single ring SRR
required	large C & wide ring	small C & large L
resonant frequency	$f_0 = \frac{1}{2\pi\sqrt{CL}}$	$f_0 < \frac{1}{2\pi\sqrt{CL}}$
magnetic response	decreased due to resistance: Rs	saturation due to the decrease of L

How to make?

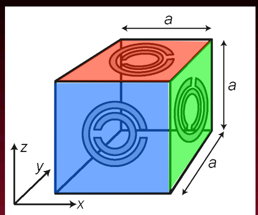
Requirements for metamaterials

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





10 trillion (10^{13}) resonators in 1 cm^{-3}

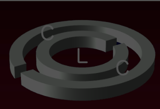
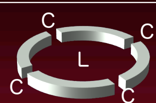


nano-scale 3D metal strcuture

+

mass producibility

Design strategy of nano-resonator

frequency	~ 100THz	100THz ~
structure	 double ring SRR	 single ring SRR
required	large C & wide ring	small C & large L
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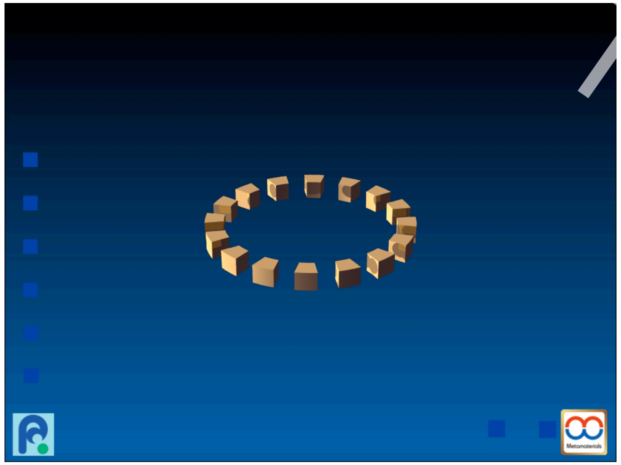

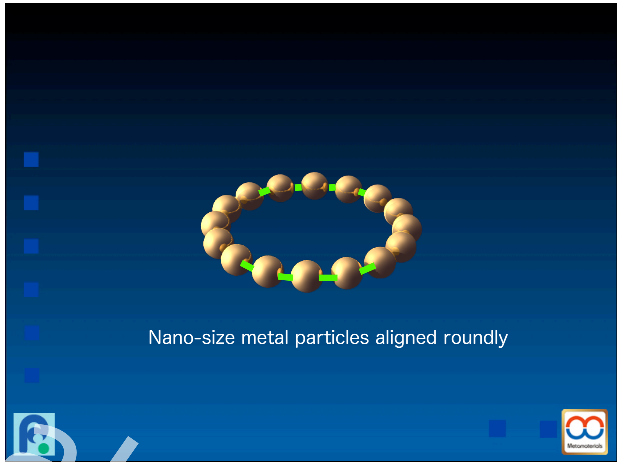

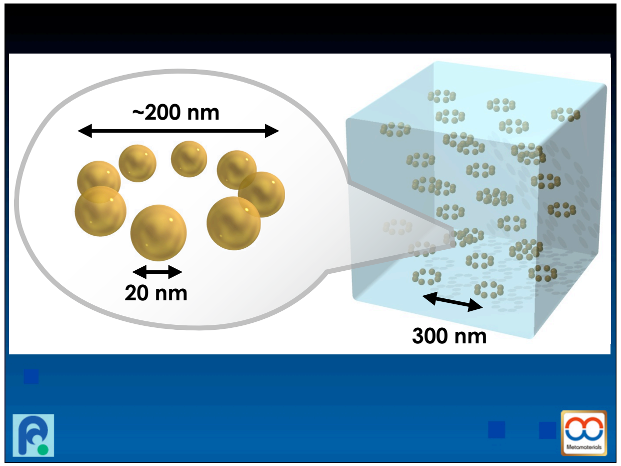

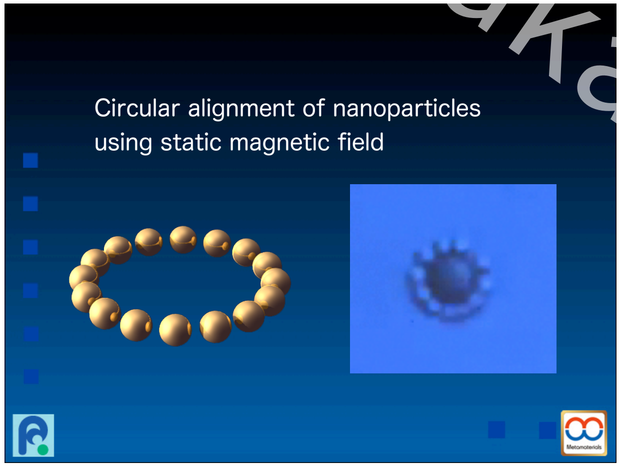

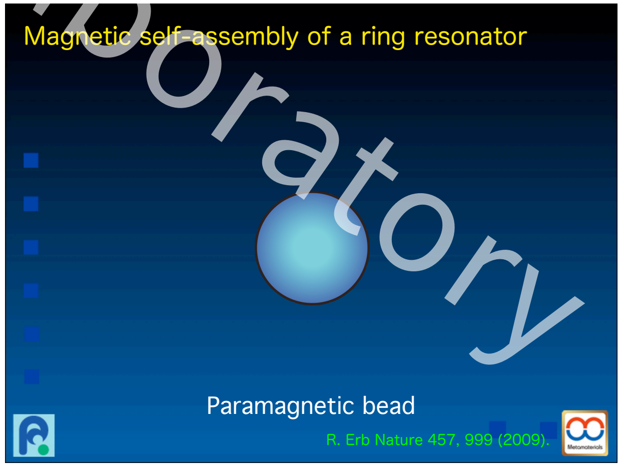

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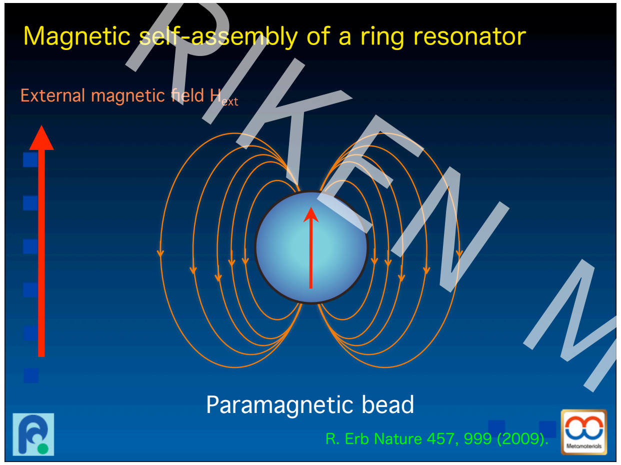

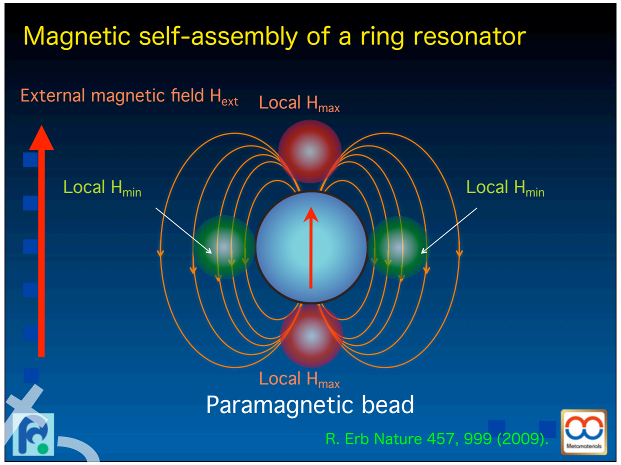

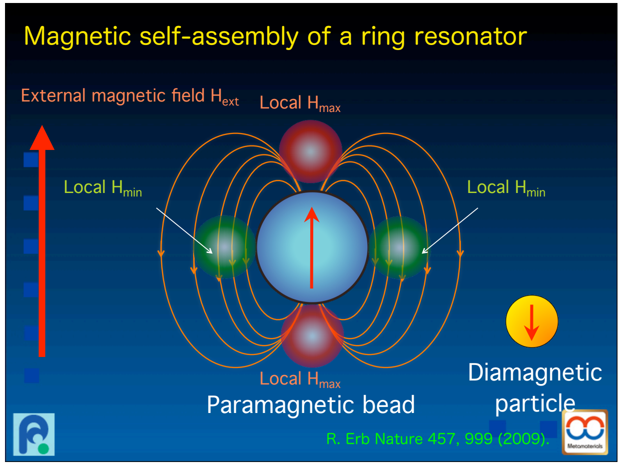

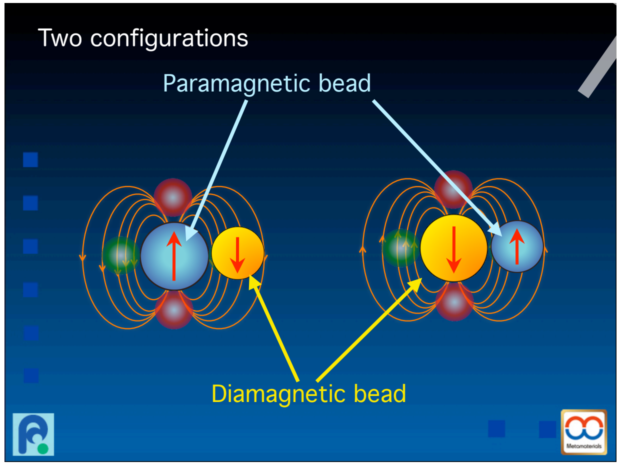

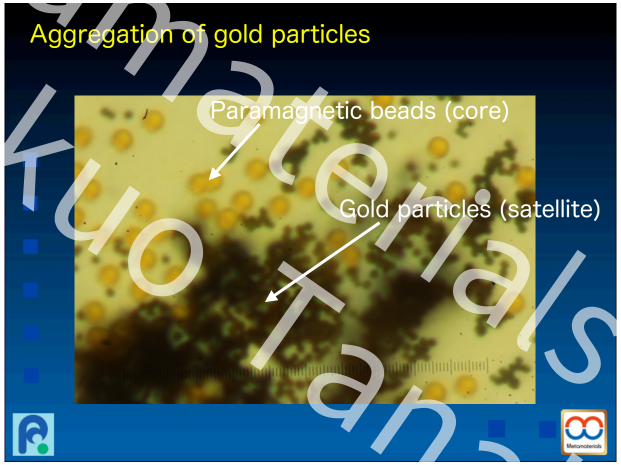

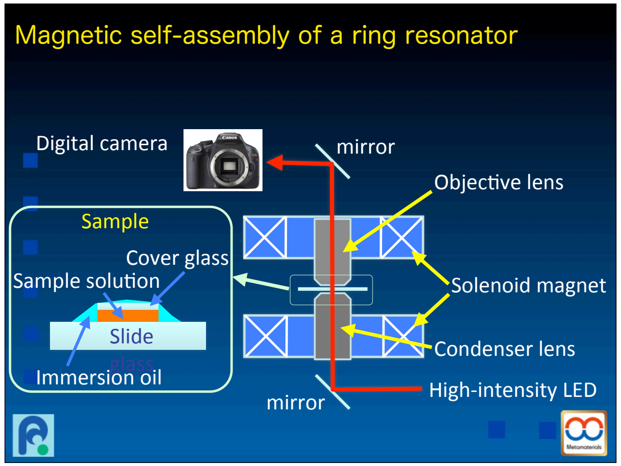

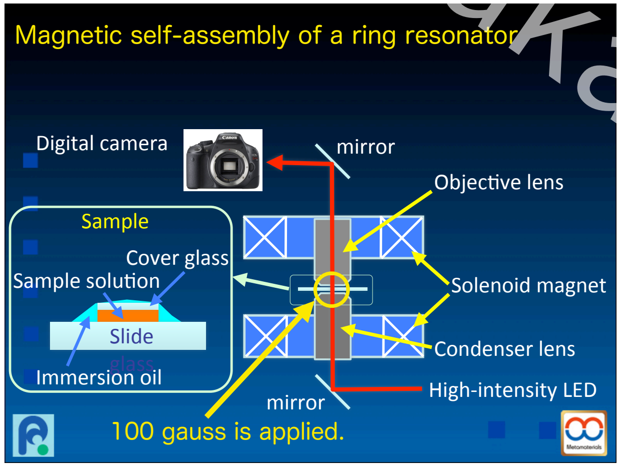

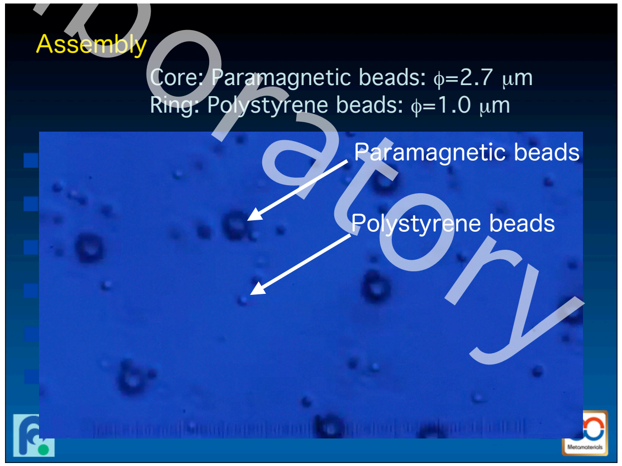

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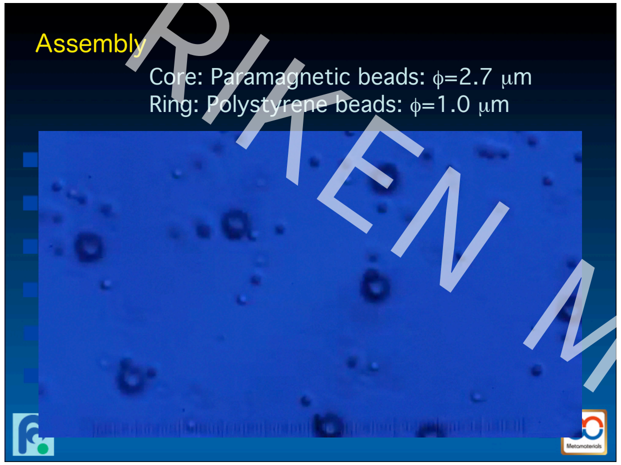
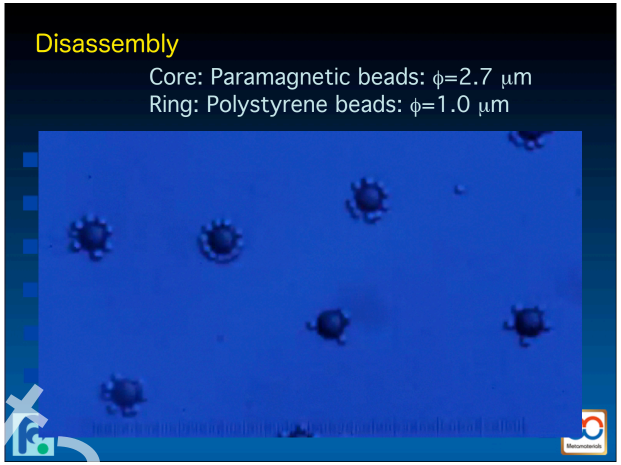
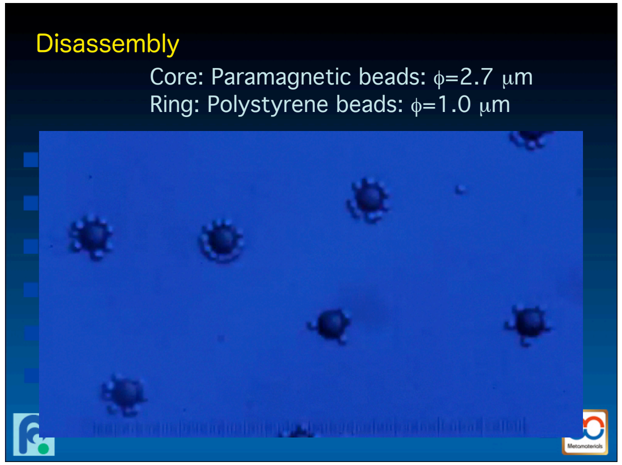
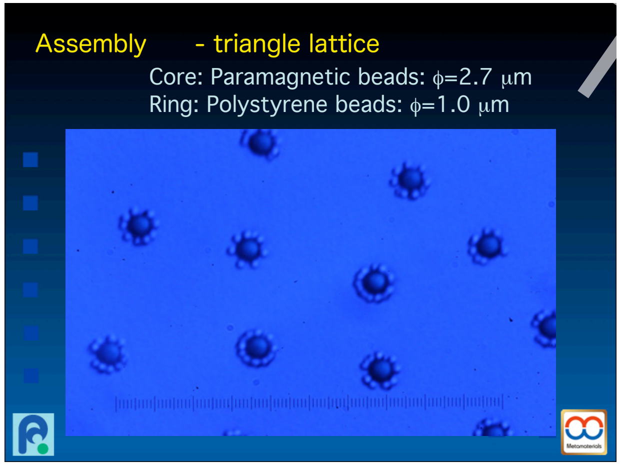
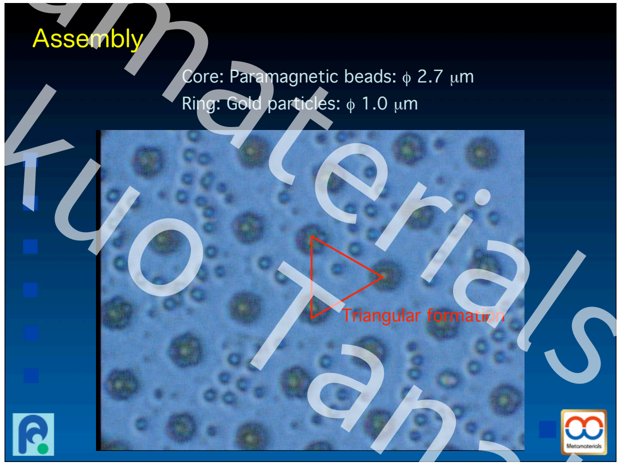
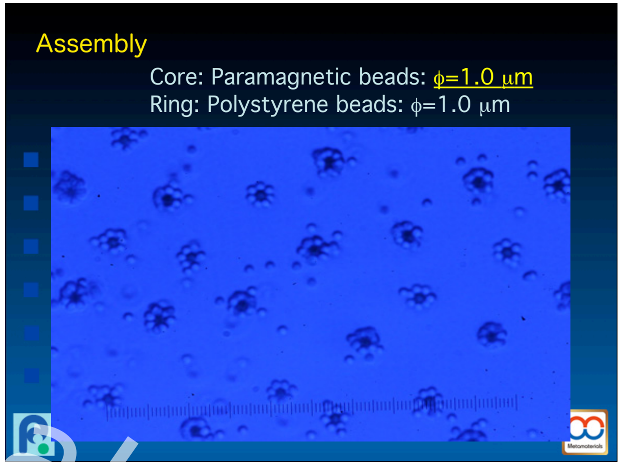

Assembly
Core: Paramagnetic beads: ϕ=2.7 μm
Ring: Polystyrene beads: ϕ=1.0 μm

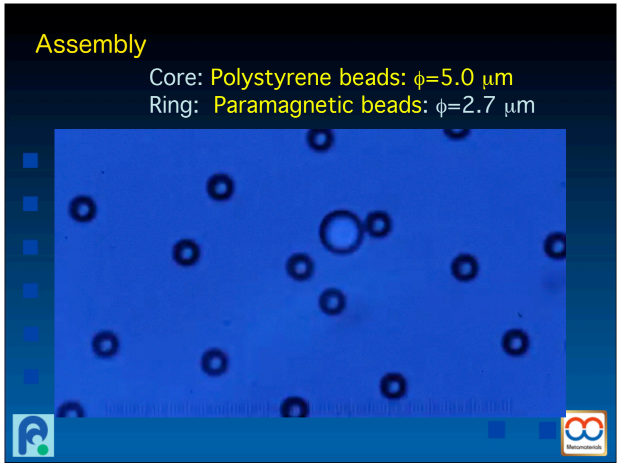

Disassembly
Core: Paramagnetic beads: ϕ=2.7 μm
Ring: Polystyrene beads: ϕ=1.0 μm

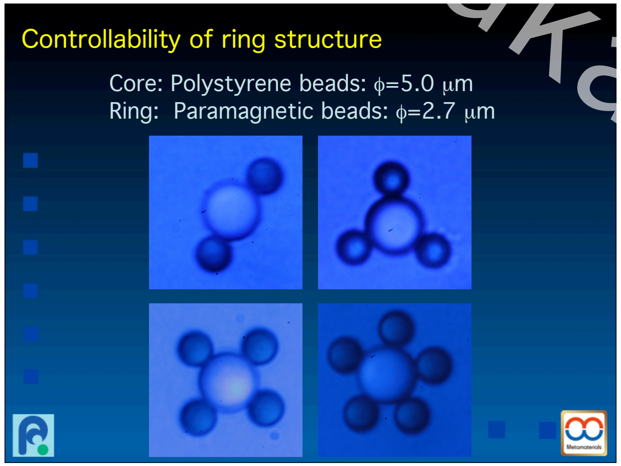

Disassembly
Core: Paramagnetic beads: ϕ=2.7 μm
Ring: Polystyrene beads: ϕ=1.0 μm

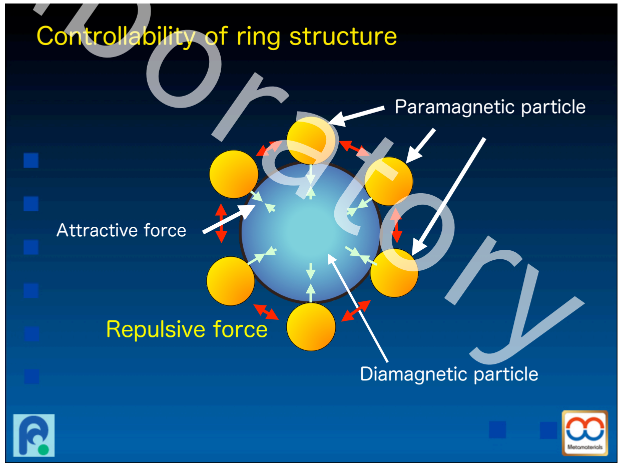

Assembly - triangle lattice
Core: Paramagnetic beads: ϕ=2.7 μm
Ring: Polystyrene beads: ϕ=1.0 μm

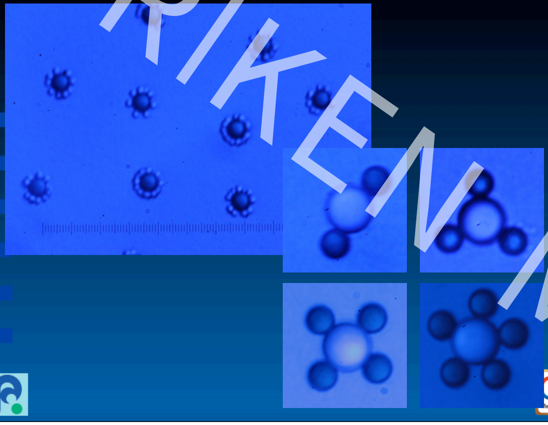

Assembly
Core: Paramagnetic beads: ϕ 2.7 μm
Ring: Gold particles: ϕ 1.0 μm
Triangular formation


Assembly
Core: Paramagnetic beads: ϕ=1.0 μm
Ring: Polystyrene beads: ϕ=1.0 μm


Assembly
Core: Polystyrene beads: ϕ=5.0 μm
Ring: Paramagnetic beads: ϕ=2.7 μm


Controllability of ring structure
Core: Polystyrene beads: ϕ=5.0 μm
Ring: Paramagnetic beads: ϕ=2.7 μm


Controllability of ring structure
Paramagnetic particle
Attractive force
Repulsive force
Diamagnetic particle



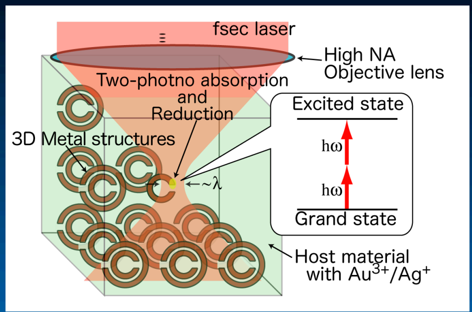
Conclusion

- Brief introduction of plasmonic metamaterials
- Fabrication techniques for 3D metamaterials
  Magnetic formation of metal ring structures

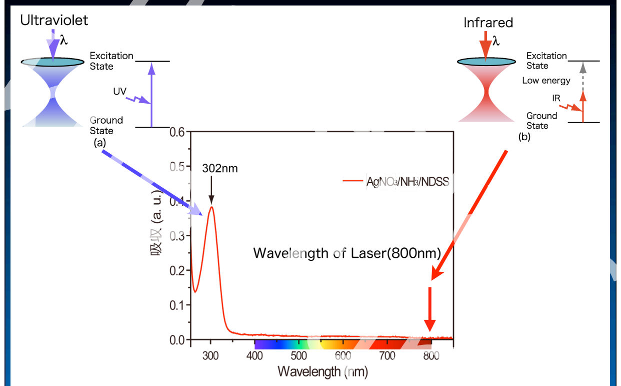
(2) Two-photon reduction technique

Two-photon reduction technique

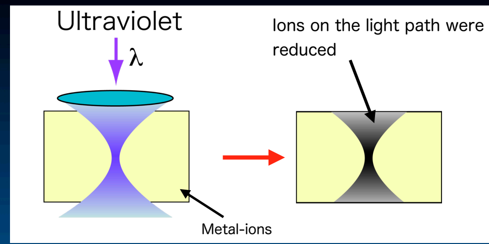
- T. Tanaka et. al, Appl. Phys. Lett. 88, 81107 (2006).
- JPN Patent Applied 2003-175819, 2005-96327
- USPatent 10/808,517



Absorption spectrum of Ag+



Irradiation UV light (One photon absorption)

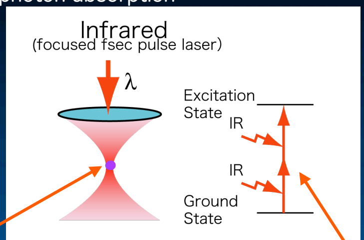


not suitable for 3D fabrication

metallize ions only at the laser beam spot.

Irradiate tightly focused fsec pulse NIR laser

Two-photon absorption

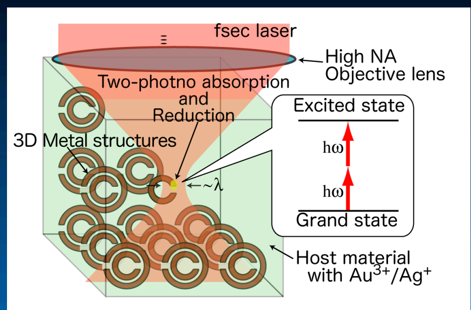


Equivalent to UV irradiation at the laser beam spot.

Energy of two photons are added.

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

Direct drawing metal structures by light spot



Gold | Silver

$AuHCl_4$ | $AgNO_3$

diameter = 10, 20μm

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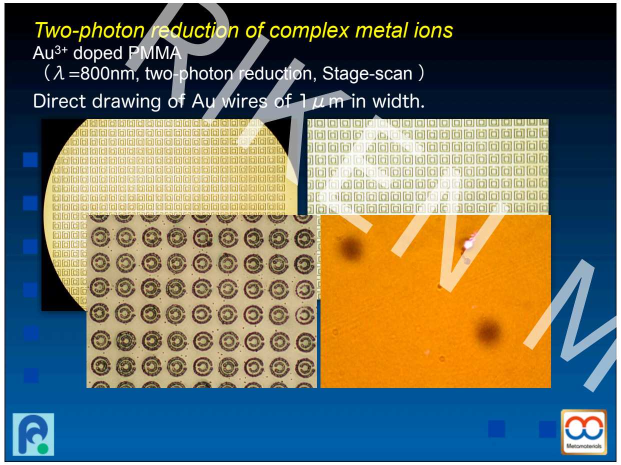
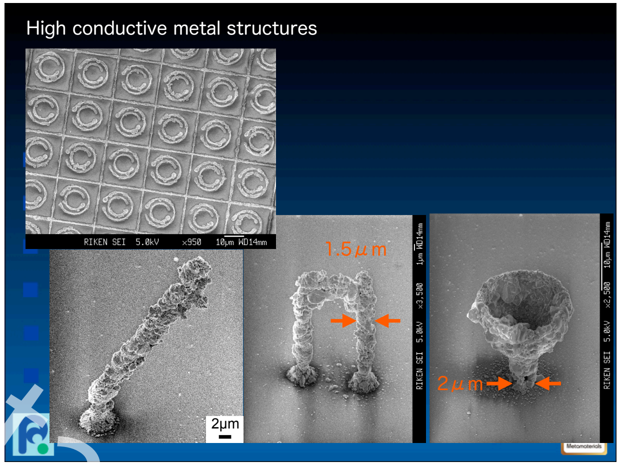
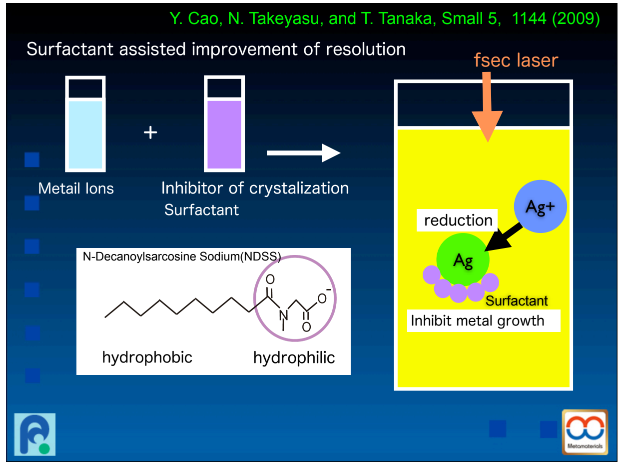
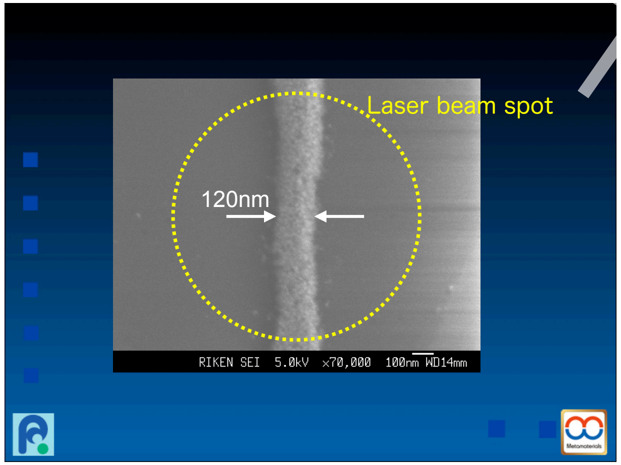
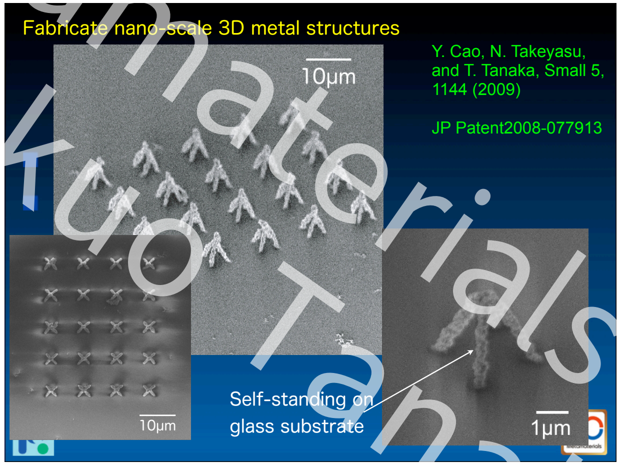
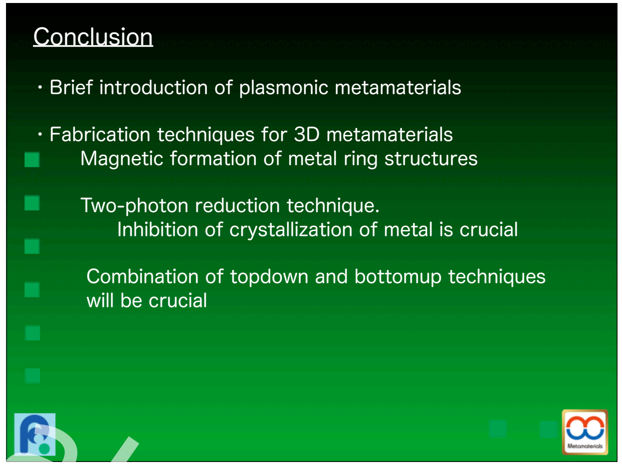

Two-photon reduction of complex metal ions
Au³⁺ doped PMMA
(λ=800nm, two-photon reduction, Stage-scan)
Direct drawing of Au wires of 1μm in width.


High conductive metal structures
1.5μm
2μm
2μm


Y. Cao, N. Takeyasu, and T. Tanaka, Small 5, 1144 (2009)
Surfactant assisted improvement of resolution
fsec laser
+
Metail Ions
Inhibitor of crystalization
Surfactant
N-Decanoylsarcosine Sodium(NDSS)
hydrophobic
hydrophilic
reduction
Ag+
Ag
Surfactant
Inhibit metal growth


Laser beam spot
120nm
RIKEN SEI 5.0kV ×70,000 100nm WD14mm


Fabricate nano-scale 3D metal structures
Y. Cao, N. Takeyasu, and T. Tanaka, Small 5, 1144 (2009)
JP Patent2008-077913
10μm
10μm
Self-standing on glass substrate
1μm


Conclusion
・Brief introduction of plasmonic metamaterials
・Fabrication techniques for 3D metamaterials
Magnetic formation of metal ring structures
Two-photon reduction technique.
Inhibition of crystallization of metal is crucial
Combination of topdown and bottomup techniques will be crucial