

Magnetic assembly of three-dimensional metamaterials

RIKEN Metamaterials Lab.
Hokkaido University Joint Lab.

Takuo Tanaka

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)

refraction, reflection, focusing, dispersion, diffraction, guiding, optical integrated circuit, scattering, rotating polarization, emission/detection,

History of optics/photronics 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 ($\mu=1.0$).

Plasma, Metal (Ag, Au), Air, Water, Glass, Diamond, Diamagnetic materials

Not exist in nature

Magnetic properties of materials is strongly restricted
No magnetic materials for light in nature

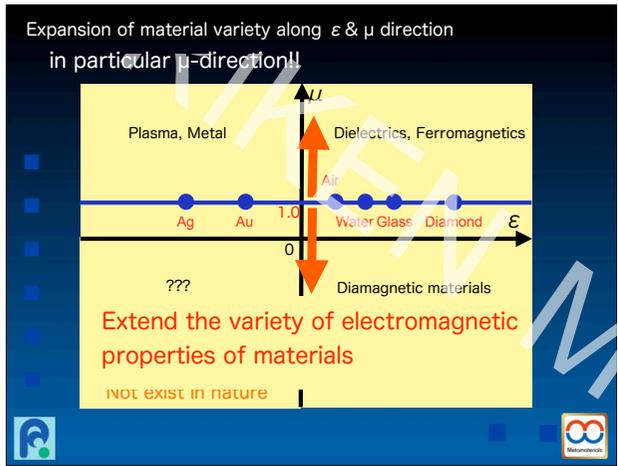
Not exist in nature

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

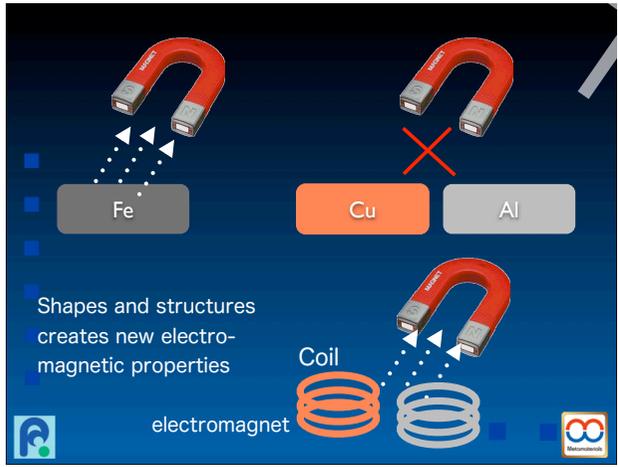
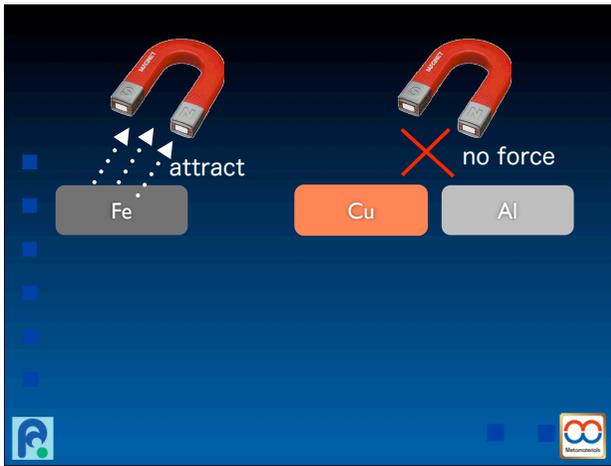
permittivity permeability

↓ in the light region

$\mu=1.0$, then n is approximated as $n = \sqrt{\epsilon}$ <in optics>



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

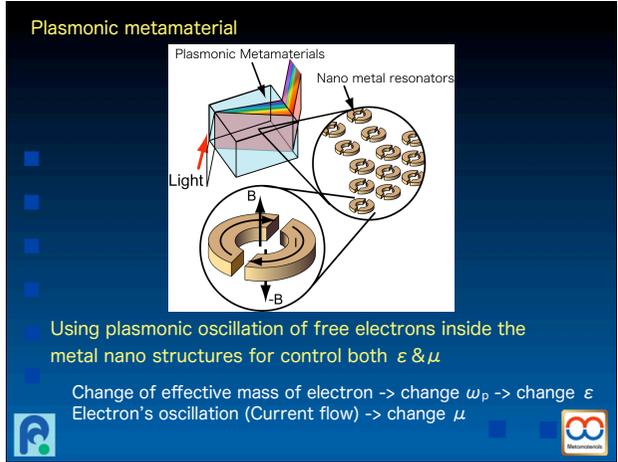
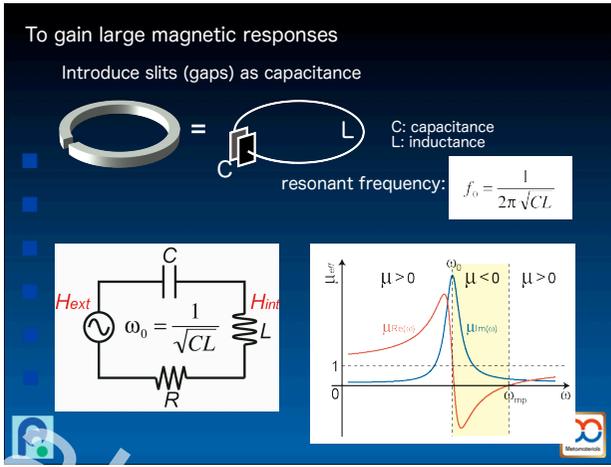


How to create artificial magnetism in high freq. band
Integrate a mechanism which creates magnetic response

Circular current
Metallic ring structure
Current (Motion/Vibration of electrons)

Applied magnetic field

Induced current: J



Theoretically investigation of metamaterials in visible region

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

PHYSICAL REVIEW LETTERS

Negative Magnetic Permeability in the Visible Light Region

Atsushi Ishikawa,^{1,2} Takao Tanaka,^{1,*} and Satoshi Kawata^{1,2}

¹Nanophotonics Laboratory, RIKEN Hirosawa, Wako, Saitama 351-0198, Japan
²Department of Applied Physics, Osaka University Yamadaoka, Suita, Osaka 565-0871, Japan
(Received 22 November 2004; revised manuscript received 31 August 2005; published 1 December 2005)

Negative magnetic permeability of single split-ring resonators (SSRRs) is theoretically investigated in the visible light region. To describe the conduction characteristics of metal in the visible range, we develop the internal impedance formula completely. In our calculation, we determine the magnetic responses of the SSRR accurately. Based on our investigations, we also demonstrate the negative μ of the silver SSRR array in the visible light region.

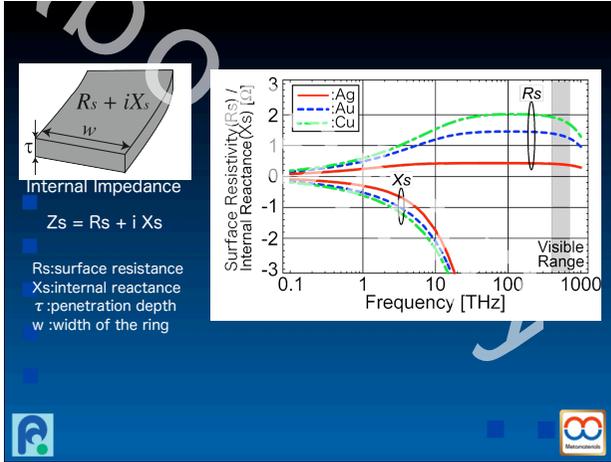
DOI: 10.1103/PhysRevLett.95.237401 PACS numbers: 78.20.Ci, 73.20.Mf, 78.20.Bh

Recently, controlling optical properties of materials by an array of metallic subwavelength-structured objects has attracted much interest from researchers. This artificial material referred to as "metamaterial" conceptually enables us to freely specify the permittivity (ϵ) and the permeability (μ) in a particular frequency region. In particular, a split-ring resonator (SRR) [1], which acts as an artificial magnetic atom, is a powerful tool for obtaining a negative μ , with which we can create a left-handed material (LHM) exhibiting unique electromagnetic phenomena [2]. By using the SRR, negative μ materials and LHMs have already been demonstrated in the microwave region [3,4].

On the other hand, in the high frequency region above

$Z_s(\omega) = \frac{1}{\sigma(\omega)\delta(\omega)} = R_s(\omega) + iX_s(\omega)$ (2)

where $\delta(\omega)$ is the skin depth [10]. The real and imaginary parts of $Z_s(\omega)$ are the surface resistivity R_s and the internal reactance X_s , respectively, in the optical frequency region. Eq. (2), including the skin effect, enables us to describe the conduction characteristics properly. However, particularly in the frequency region above 100 THz, which is our interest, we must consider not only the delay of the current but also the displacement current inside the metal. To describe these phenomena, we derived the following equation for the internal impedance of the plane conductor from the Maxwell's equations without any approximation:



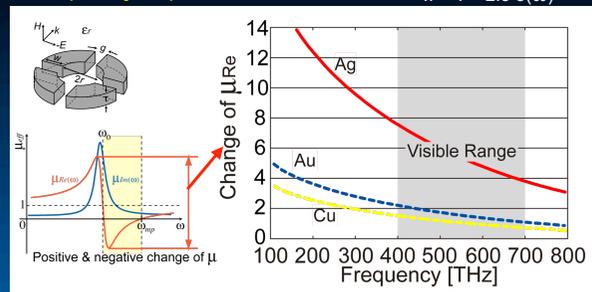
Internal Impedance
 $Z_s = R_s + iX_s$
 R_s : surface resistance
 X_s : internal reactance
 τ : penetration depth
 w : width of the ring

Properties of metals

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

F : filling factor
 C_g : geometrical capacitance
 L_g : geometrical inductance
 $Z(\omega)$: impedance of the circuit

frequency dependence of μ_{Re}



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

l is fixed

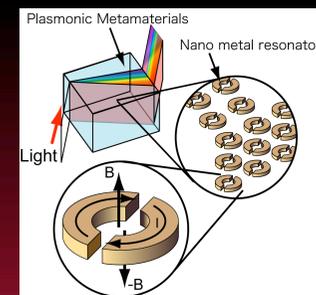
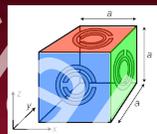
Design strategy of nano-resonator

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: R_s	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 should be well designed
resonant frequency -> C, L
3. Array
Three-dimensional array structure



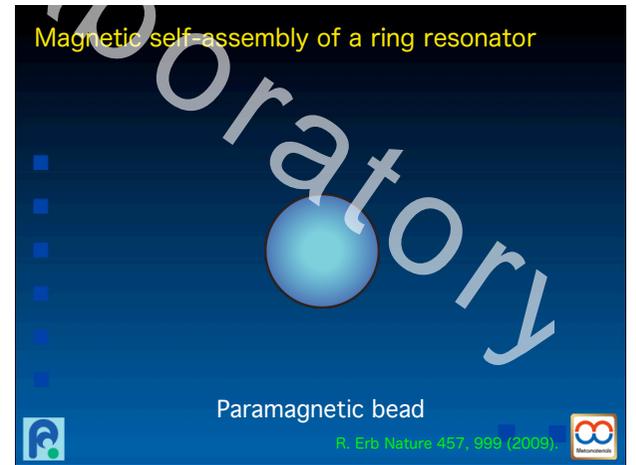
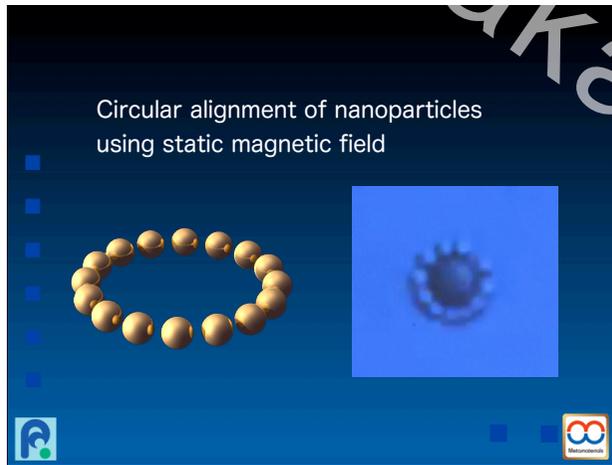
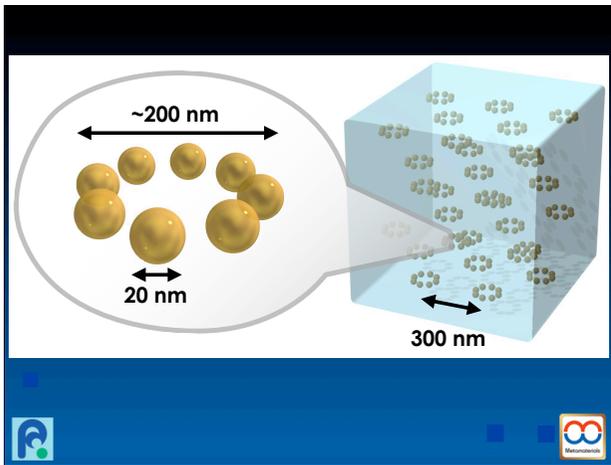
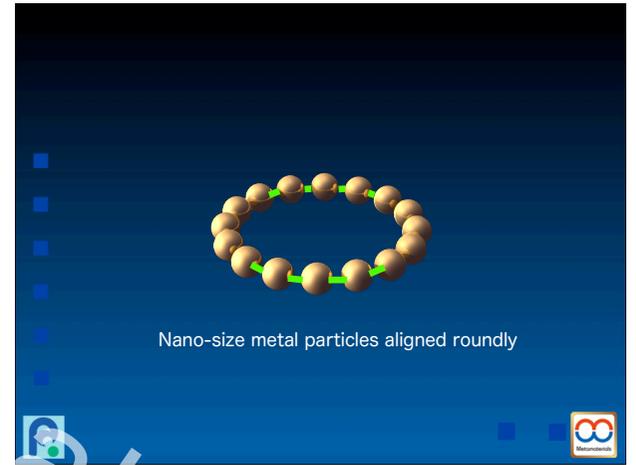
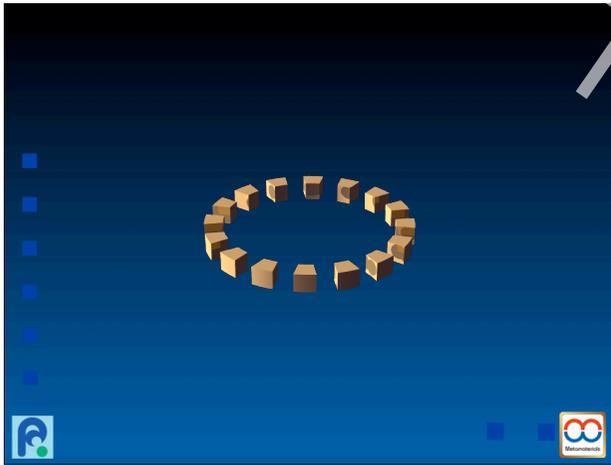
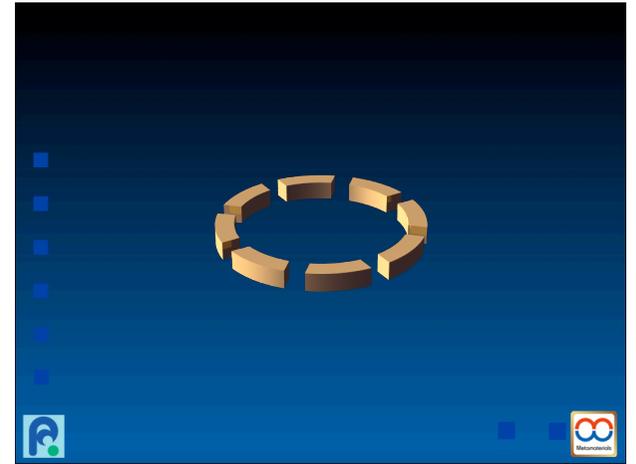
10 trillion (10^{13}) resonators in 1 cm^3

nano-scale 3D metal structure
+ 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
resonant frequency	$f_0 = \frac{1}{2\pi\sqrt{CL}}$	$f_0 < \frac{1}{2\pi\sqrt{CL}}$
magnetic response	decreased due to resistance: R_s	saturation due to the decrease of L

laboratory



Magnetic self-assembly of a ring resonator

External magnetic field H_{ext}

Paramagnetic bead

R. Erb Nature 457, 999 (2009)

Magnetic self-assembly of a ring resonator

External magnetic field H_{ext} Local H_{max}

Local H_{min}

Paramagnetic bead

R. Erb Nature 457, 999 (2009)

Magnetic self-assembly of a ring resonator

External magnetic field H_{ext} Local H_{max}

Local H_{min}

Paramagnetic bead

Diamagnetic particle

R. Erb Nature 457, 999 (2009)

Two configurations

Paramagnetic bead

Diamagnetic bead

Diamagnetic bead

Aggregation of gold particles

Paramagnetic beads (core)

Gold particles (satellite)

Polystyrene beads have better dispersibility

Magnetic self-assembly of a ring resonator

Digital camera

mirror

Objective lens

Sample

Cover glass

Sample solution

Slide

Immersion oil

Solenoid magnet

Condenser lens

High-intensity LED

Magnetic self-assembly of a ring resonator

Digital camera

mirror

Objective lens

Sample

Cover glass

Sample solution

Slide

Immersion oil

Solenoid magnet

Condenser lens

High-intensity LED

100 gauss is applied.

Assembly

Core: Paramagnetic beads: $\phi=2.7 \mu\text{m}$

Ring: Polystyrene beads: $\phi=1.0 \mu\text{m}$

Paramagnetic beads

Polystyrene beads

Assembly

Core: Paramagnetic beads: $\phi=2.7 \mu\text{m}$
 Ring: Polystyrene Beads: $\phi=1.0 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. Each structure consists of a larger central core surrounded by a ring of smaller particles.

Disassembly

Core: Paramagnetic beads: $\phi=2.7 \mu\text{m}$
 Ring: Polystyrene beads: $\phi=1.0 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. The structures appear to be breaking apart, with the smaller ring particles separating from the larger central cores.

Disassembly

Core: Paramagnetic beads: $\phi=2.7 \mu\text{m}$
 Ring: Polystyrene beads: $\phi=1.0 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. The structures appear to be breaking apart, with the smaller ring particles separating from the larger central cores.

Assembly - triangle lattice

Core: Paramagnetic beads: $\phi=2.7 \mu\text{m}$
 Ring: Polystyrene beads: $\phi=1.0 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. The structures are arranged in a regular, triangular lattice pattern.

Assembly

Core: Paramagnetic beads: $\phi=2.7 \mu\text{m}$
 Ring: Gold particles: $\phi=1.0 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. The structures are arranged in a regular, triangular lattice pattern. A red triangle is drawn over one of the structures, with the text "(Triangular formation)" next to it.

Assembly

Core: Paramagnetic beads: $\phi=1.0 \mu\text{m}$
 Ring: Polystyrene beads: $\phi=1.0 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. Each structure consists of a smaller central core surrounded by a ring of smaller particles.

Assembly

Core: Polystyrene beads: $\phi=5.0 \mu\text{m}$
 Ring: Paramagnetic beads: $\phi=2.7 \mu\text{m}$

Micrograph showing several dark, circular structures on a blue background. Each structure consists of a larger central core surrounded by a ring of smaller particles.

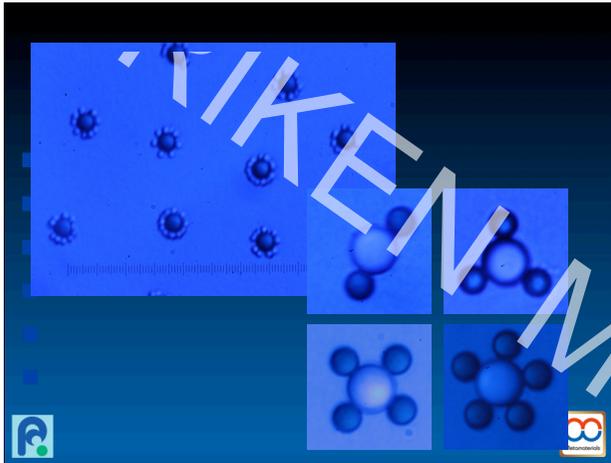
Controllability of ring structure

Core: Polystyrene beads: $\phi=5.0 \mu\text{m}$
 Ring: Paramagnetic beads: $\phi=2.7 \mu\text{m}$

Micrograph showing four small images arranged in a 2x2 grid. Each image shows a different configuration of a central core surrounded by a ring of smaller particles, illustrating the controllability of the ring structure.

Controllability of ring structure

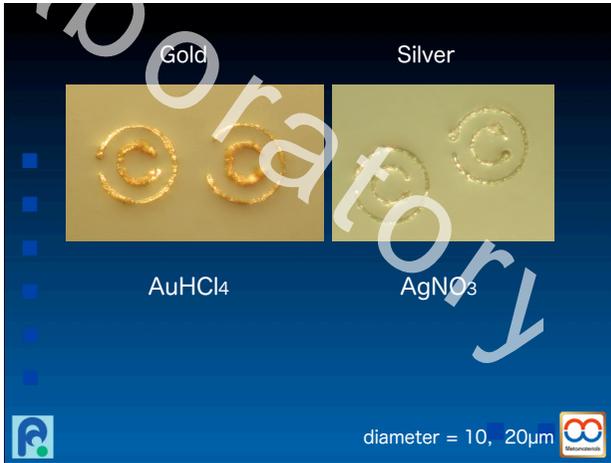
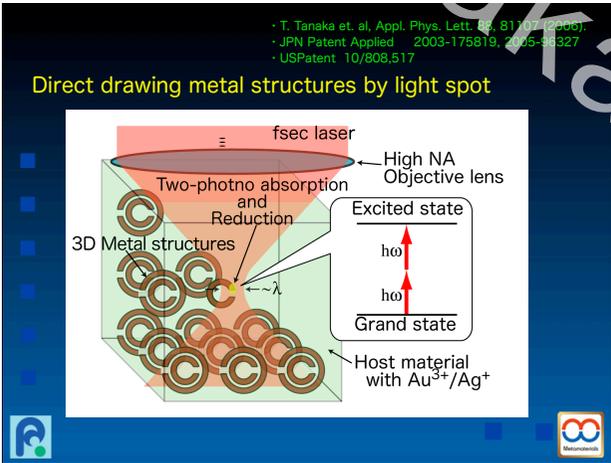
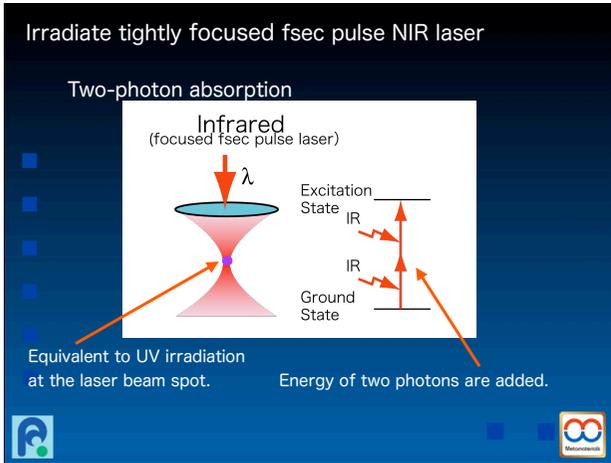
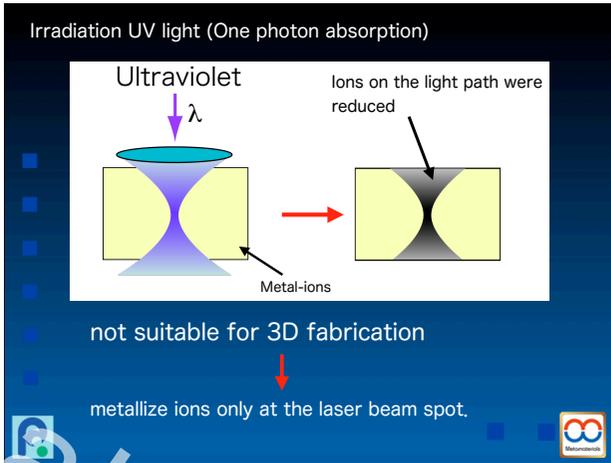
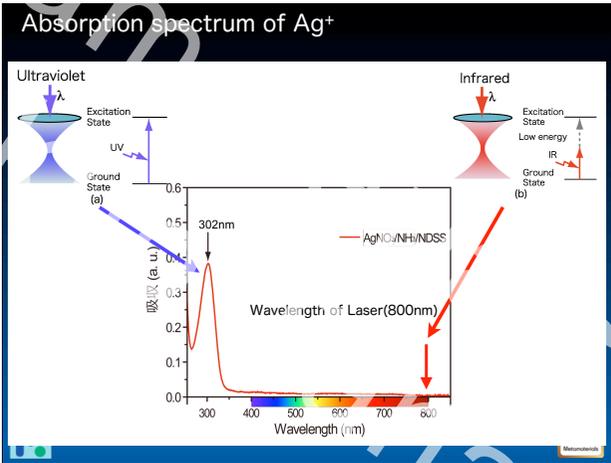
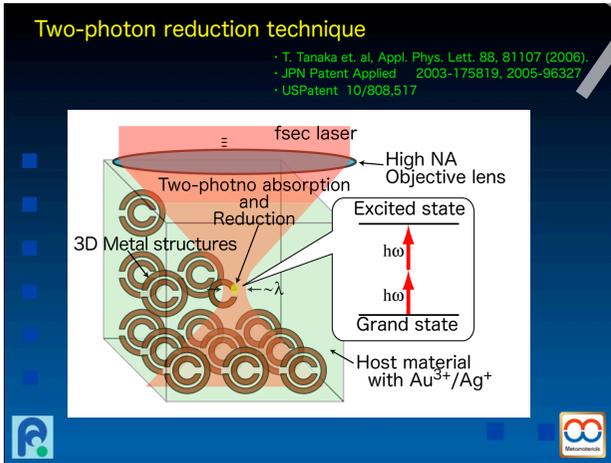
Diagram illustrating the forces acting on a central core (Diamagnetic particle) surrounded by a ring of smaller particles (Paramagnetic particles). Attractive forces (red arrows) pull the paramagnetic particles towards the central core, while repulsive forces (white arrows) push the paramagnetic particles away from each other, forming a ring.



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

The image shows a series of SEM images of Au wires. The top left shows a grid of small circular patterns. The bottom left shows a larger grid of similar patterns. The right side shows a close-up of a single Au wire with a diameter of 1 μm. A schematic diagram illustrates the two-photon reduction process where a laser beam is focused on a surface, creating a small volume where Au³⁺ ions are reduced to Au⁰ and form a wire.

High conductive metal structures

The image displays several SEM images of high-conductive metal structures. The top left shows a grid of circular patterns. The bottom left shows a long, thin wire. The middle shows a ring structure with a diameter of 1.5 μm. The right shows a larger, more complex structure with a diameter of 2 μm. The images are labeled with 'RIKEN SEI 5.0kV x950 10μm WD14nm' and '2μm'.

Surfactant assisted improvement of resolution
 Y. Cao, N. Takeyasu, and T. Tanaka, Small 5, 1144 (2009)

The diagram illustrates the process of surfactant-assisted improvement of resolution. It shows a mixture of Metal Ions and Inhibitor of crystallization Surfactant. The surfactant is N-Decanoylsarcosine Sodium (NDSS), which has a hydrophobic tail and a hydrophilic head. The surfactant molecules are shown surrounding Ag⁺ ions, forming a complex that inhibits metal growth. The process is initiated by a femtosecond (fsec) laser, leading to the reduction of Ag⁺ to Ag⁰ and the formation of a small metal structure.

The image shows a laser beam spot on a surface. The spot is circular and has a diameter of 120 nm. The image is labeled with 'Laser beam spot' and '120nm'. The SEM parameters are 'RIKEN SEI 5.0kV x70,000 100nm WD14nm'.

Fabricate nano-scale 3D metal structures
 Y. Cao, N. Takeyasu, and T. Tanaka, Small 5, 1144 (2009)
 JP Patent2008-077913

The image shows several SEM images of nano-scale 3D metal structures. The top left shows a grid of small structures. The middle shows a larger structure with a diameter of 10 μm. The bottom right shows a self-standing structure on a glass substrate with a diameter of 1 μm. The images are labeled with '10μm' and 'Self-standing on glass substrate'.

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