# Towards three-dimensional isotropic metamaterials

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**Abstract**

The electromagnetic properties and design strategy of plasmonic metamaterials in the optical spectral range are theoretically investigated. The laser fabrication technique for the three-dimensional isotropic metamaterials is also proposed. Three-dimensional nanometer-scale silver or gold structures are demonstrated.

## 1. Introduction

Plasmonic metamaterials are artificially designed materials whose electromagnetic properties come from their structure. By engineering such materials, we can control their magnetic permeability even in the optical frequency region in which their relative permeability is fixed at unity. In this paper, we report on the theoretical investigations of the appropriate structures of plasmonic metamaterials that work in the visible light frequency region. Moreover, we present a novel laser fabrication technique using two-photon-induced metal-ion reduction for creating three-dimensional isotropic metamaterials.

## 2. Theory for design of plasmonic metamaterials in visible light region

We have theoretically investigated the plasmonic metamaterial structure that works as the artificially magnetic materials in the optical frequency region [1-4]. Figure 1 shows the split ring-resonator (SRR) model used in our calculations. We derived the effective permeability ($\mu_{eff}$) of the SRRs and calculated the frequency dispersion of $\mu_{eff}$ from 100THz to 800THz covering the entire visible light frequency region taking into account the electro-magnetic properties of the metals (silver, gold, and copper). Figure 2 shows the calculation results of dispersion properties of the change of $\mu_{eff}$ for each metal SRRs array. From the results we have clarified that a three-dimensional array of split-ring-resonators made of silver can give a strong magnetic response in the visible light frequency region. As also shown in Fig. 2, silver SRRs exhibit $\mu_{eff}$ changes exceeding 2.0 in the entire visible range, which means $\mu_{eff}$ can become a negative value, while the responses of gold and copper SRRs do not exceed 2.0 in the visible light region.

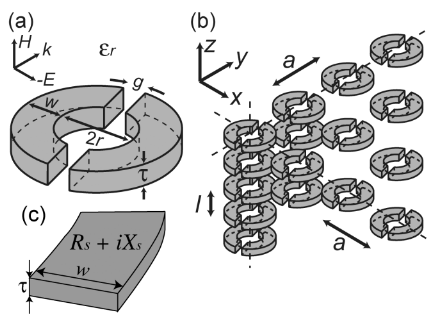


Fig. 1: Models of metamaterial structure used in calculations.

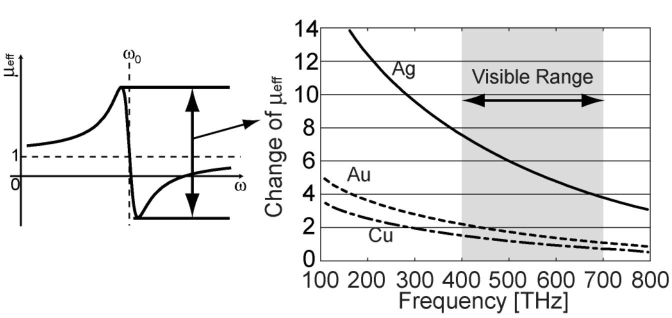


Fig. 2: Frequency dependencies of the change of effective permeability ($\mu_{eff}$) of SRRs made of silver, gold, and copper.

## 3. Two-photon reduction technique for 3D metal structures

To create an isotropic metamaterial, the fabrication technique requires the ability to make arbitrary three-dimensional nano-scale metallic structures. To satisfy this requirement, we have proposed a new fabrication technique that uses two-photon induced reduction of metallic complex ions [5-8]. Figure 3 shows a schematic of this two-photon-induced reduction technique. A mode-locked Ti:Sapphire laser system with a center wavelength of 800 nm was used as a light source. The laser beam was focused inside the metal-ion solution using a high NA oil-immersion objective lens. The focused laser beam was scanned in two dimensions (x-y scanning) using a pair of galvanometer mirrors, and was also scanned in the longitudinal direction (z-scanning) by translating the objective lens using a motor stage.

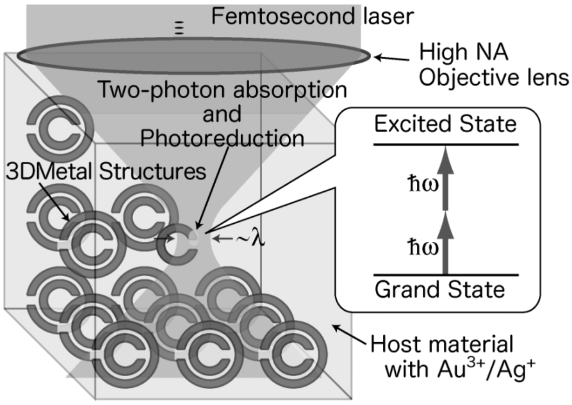


Fig. 3: Schematic of two-photon-induced metal-ion reduction.

Figure 4 (a) and (b) show the experimental result of 3D silver structures standing on glass substrate. Fig. 4(c) shows a gold resonator array structure directly fabricated in PMMA film in which $Au^{3+}$ ions are doped. Recently, in order to improve the spatial resolution of the technique down to the nano-mater scale by controlling the growth process of nano-metal-crystals, we added a n-decanoylsarcosine sodium (NDSS) in the silver ions solution as an inhibitor of the metal crystal growth, and we success-fully achieved a spatial resolution of 100 nm [9, 10]. Fig. 4 (d) shows the 3D silver pyramid metal structures with 200nm linewidth fabricated using a silver ion aqueous solution with NDSS. This nano-meter scale resolution was achieved by the metal crystallization control using dopant surfactant mole-cules. While the linewidth of the pillar was around 200 nm, these structures have sufficient physical strength to resist the surface tension in the washing process and electric conductivity.

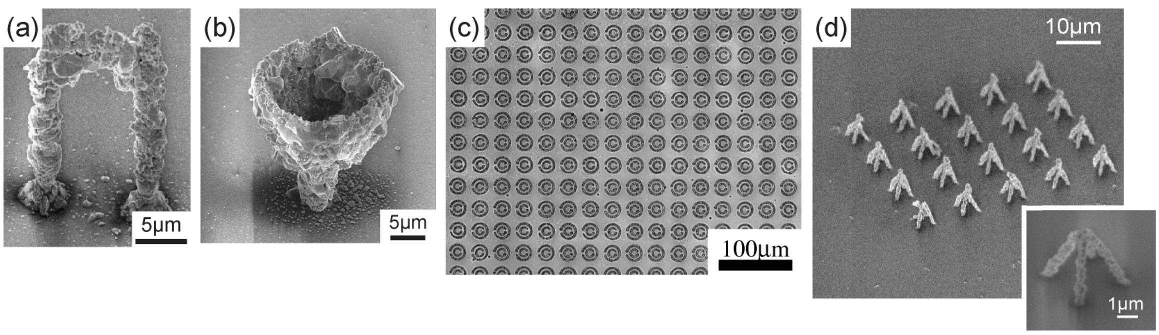


Fig. 4: 2D and 3D metal structures fabricated by two-photon reduction technique

## 4. Towards metaphotonics

In the end, we want to emphasize the potential ability of plasmonic metamterials. As is well known, conventional optics deal with materials on a line of relative magnetic permeability of 1.0 (Figure 5(a)). This is a one-dimensional, very small world. The use of metamaterials with various magnetic permeabilities would greatly expand the variety of electromagnetic properties of the materials and open the door to the new field of optics and photonics. We named the new field of academic study that deals with the wide world of optics "metaphotonics" (Fig.5 (b)). The new field transcends the world of conventional optics and photonics, but nobody knows what will happen in it. We will discover unknown phenomena and unexpected treasures buried in the wide world of light.

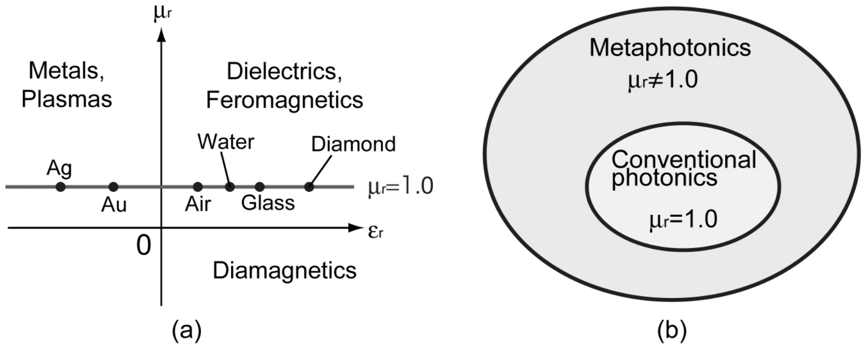


Fig. 5: Metaphotonics

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