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# Characterizations of an infrared polarization-insensitive metamaterial perfect absorber and its potential in sensing applications

Nguyen Thanh Tung[a,b,*], Takuo Tanaka[b]

[a] *Institute of Materials Science and Graduate University of Science and Technology, Vietnam Academy of Science and Technology, Hanoi, Viet Nam*
[b] *Metamaterials Laboratory, RIKEN, Saitama, Japan*

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ABSTRACT

An increasing interest has been paid for metamaterial perfect absorbers, which offer attractive platforms for electromagnetic radiation based sensing applications. In this paper, we systematically characterize an infrared polarization-insensitive metamaterial absorbers by means of finite integration simulations and spectroscopic experiments. The metamaterial absorber is composed of symmetric disk-type metal-dielectric-metal structure, which shows a near-unity absorption peak at about 70 THz. It is found that the absorption frequency can be well predicted using the magnetic resonance theory while the dielectric-thickness dependent absorptivity can only be explained by the destructive interference theory. Spectral analysis reveals the possibility of using the proposed absorber as a high-performance refractive-index and thickness sensor for novel sensitive IR inspection technologies.



## 1. Introduction

The electromagnetic properties of conventional materials essentially depend on their chemical compositions rather than on the sample shape. Nevertheless, a new class of artificial materials, the so-called metamaterials, that is made up by arrangement of sub-wavelength structures [1], reveals a very different and fascinating picture. Manipulating geometrical parameters of metamaterials can induce peculiar electromagnetic properties like, but not limited to, negative refraction, light bending, light trapping, and reversed Cherenkov radiation [2]. These fantastic electromagnetic responses are governed by the strong plasmonic behavior in metallic resonators, whose strength and frequency can be tuned nearly at will by engineering their structures [3]. While a high transmitivity are often desired for most of metamaterial applications, an increasing attention has been paid for the absorption loss due to its importance to those concerning electromagnetic radiation probing technologies [4–7]. In this regard, the concept of metal/dielectric/metal metamaterial absorbers (MMAs) has been recently introduced by Landy and coworkers [8]. The fundamental physics behind the unique absorbance of metamaterials has been attributed to the theory of magnetic resonance, where loss generated by antisymmetric oscillating currents between coupled metal structures and their induced images in the metal mirror. Simultaneously, the back reflection is terminated by matching their impedance to that of free space [9]. If one ignored the importance of structural details in metamaterials, the underlying absorption mechanism can also be understood by the destructive interference between the direct reflection and the following ones [10]. So far, the implementation of MMAs has shown obvious benefits over conventional materials in many functional aspects, for instance, further miniaturization, broader absorption band, frequency selectivity, strength tunability, and increased effectiveness [11]. In particular, nonlinear elements integrated into metamaterials with a real-time controlled absorption using external means have been intensively studied for active electromagnetic purposes [12–17]. Several approaches have been applied to realize the wide operating band feature [18–23]. Geometry-unrestricted optimization has been carried to search for isotropic MMAs that allow electromagnetic waves to be absorbed from both sides of the sample plane [24–26]. The operating frequency of MMAs has been demonstrated to be selectable from MHz wave to optical regime by scaling structural sizes [11].

Since the MMA could offer unique absorption properties with a strong plasmonic enhancement, a number of their potential applications operating in the infrared regime has been proposed, such as high-efficiency thermal emitter, high-sensitive bio-chemical sensing and molecular detecting [27–29]. To that end, a variety of infrared MMAs has been designed and inves-

* Corresponding author at: Institute of Materials Science and Graduate University of Science and Technology, Vietnam Academy of Science and Technology, Hanoi, Viet Nam.
*E-mail addresses:* tungnt@ims.vast.ac.vn (N.T. Tung), t-tanaka@riken.jp (T. Tanaka).

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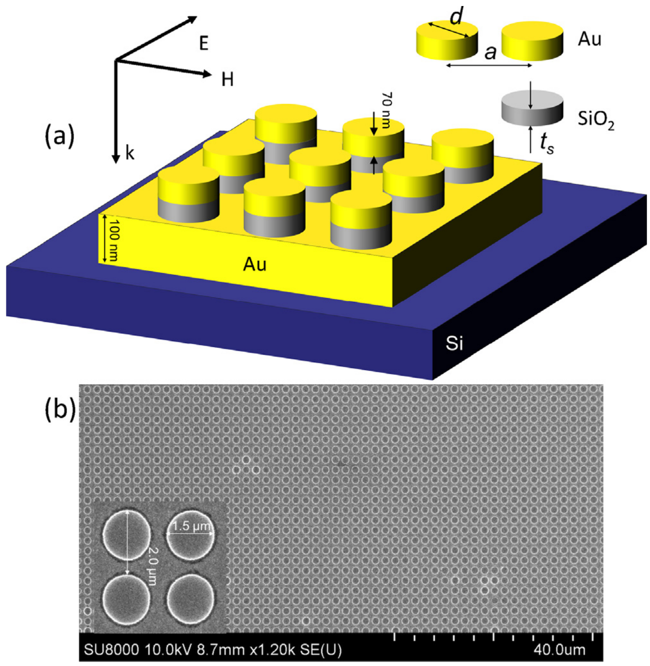


**Fig. 1.** (a) The schematic drawing of a disk-shaped MMA consisting of a $SiO_2$ layer sandwiched by a 70 nm Au pattern on top of 100 nm Au film. The whole structure is formed on the surface of a Si substrate after the deposition of a 5-nm Cr adhesion layer (not shown here). (b) A SEM image of a typical sample with a disk diameter $d$ of 1.5 and a periodicity $a$ of 2.0 μm.

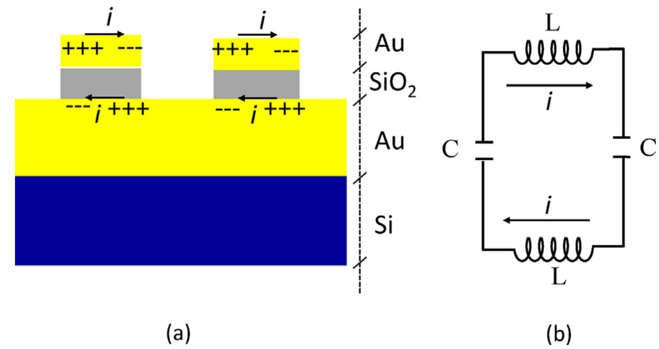


**Fig. 2.** (a) The antiparallel distribution of induced surface currents at the absorption frequency. (b) The corresponding equivalent circuit model of disk-shaped MMAs.

tigated. The first micro-structured MMA was reported in 2008 by scaling its millimeter-sized counterpart, showing an absorption of 70% at 1.5 THz [30]. For polarization-independent purposes, MMA structures evolve to four-fold rotation symmetries including split-ring structure, square-ring structure, L-shaped structure, and cross-shaped structure [31–36]. Higher symmetric but easy-to-implement structures like disk-shaped resonators and their analog forms have recently come under the spotlight as an optimal design for infrared MMAs [11,37–43]. Unfortunately, despite of numerous experimental and computational studies reported, a systematic investigation on their absorption feature has not yet been experimentally carried out. In this paper, we set out to numerically and experimentally investigate a simple polarization-insensitive disk-shaped MMAs operating at infrared frequencies. The geometrical dependency of absorption features is computed and verified by spectroscopic experiments. Our results also imply that the absorption features of the proposed MMAs are highly sensitive to the ambient properties and potential for future sensing applications.

## 2. Experimental and computational setup

A computational unit cell of the disk-shaped MMA structure is illustrated in Fig. 1(a). The structure, which is designed to fit with the fabricated samples, is composed of a disk-shaped Au resonator on top of a Au ground plate, separated by a $SiO_2$ dielectric spacer. The periodicities in the lateral (**E** and **H**) directions are denoted by $a$ while the disk diameter is labeled as $d$. The thicknesses of Au resonators and the ground plate are fixed at 70 and 100 nm, respectively, while that of the $SiO_2$ dielectric spacer is $t_s$. The dielectric constant of $SiO_2$ is assumed to be 1.96 with a loss tangent of 0.002 [44,45]. The whole structure is then embedded in a reference medium, chosen as vacuum. The numerical simulations are performed using the finite integration technique (CST Microware Studio) [46], in which the unit cell boundary condition is applied in **E** and **H** directions. A waveguide port is used to generate transverse electromagnetic plane waves perpendicularly to the sample plane. The absorption defined as $A = 1 - T - R = 1 - |S_{21}|^2 - |S_{11}|^2$ can be calculated from simulated transmission and reflection. Since the electromagnetic waves cannot penetrate through the metallic ground plate, the silicon substrate, which is actually used to hold the samples in experiments, is ignored in simulations.

The fabrication process is carried out with electron-beam evaporation of a 100-nm Au film onto a silicon substrate after a 5-nm Cr adhesion layer. Using the maskless UV-lithography technique (DL1000, Nano System Solutions), which might allow to obtain a metamaterial with an operating area of up to few $cm^2$ [29], a 2D array of periodic disk-shaped structures is patterned on the Au film surface. The final structure is then obtained after $SiO_2$ and Au films deposition and lift-off process. Fig. 1(b) shows the scanning electron microscope (SEM) image of a fabricated sample, in which $d = 1.5$ μm and $a = 2.0$ μm. The absorption property of the MMA is characterized using a Fourier-transformed infrared spectrometer (FTIR 6300FV, Jasco). To achieve a better signal-to-noise ratio of IR signals, the sample chamber is purged with dry nitrogen gas and a liquid nitrogen-cooled high-sensitive MCT (HgCdTe) detector is used with the frequency resolution of 2 $cm^{-1}$. As mentioned above, due to the presence of the thick Au film, no transmittance is measured and only reflectance measurement is performed. The recorded reflection spectra of the metamaterial samples are calibrated by that of a bare Au reference sample.

## 3. Equivalent circuit model

In order to formulate how geometrical parameters influence the resonant frequency of the proposed MMAs, their charge distribution is analyzed to construct an equivalent circuit model. The use of equivalent circuit models has been demonstrated as one of the most effective methods in describing the electromagnetic response of metamaterials [12,25,47,48]. For MMAs, it is common that the charge currents are induced between the metamaterial resonators and their images on the metallic plate as illustrated in Fig. 2(a) [11]. These stimulated currents are distributed in an antiparallel form, which might be coupled to an incident time varying magnetic field to yield a Lorentz-like magnetic response. The magnetic resonance is thus associated with the absorption behavior and the magnetic resonant frequency can be used to determine the absorption frequency.

The equivalent circuit for the magnetic mode of the Au/$SiO_2$/Au disk-shaped MMA structure is modeled as seen in Fig. 2(b). The magnetic resonant frequency can be estimated from the inductance $L$ and the capacitance $C$ [49]. The interactions between adjacent unit cells are small compared with the intra-structure interactions and