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# LITHOGRAPHIC FABRICATION AND SPECTROSCOPIC CHARACTERIZATION OF A THz METAMATERIAL ADSORBER

**Le Hong Phuc[1], Nguyen Thanh Tung[2, 3, *]**

[1]*School of Engineering Physics, Hanoi University of Science and Technology, 1 Dai Co Viet, Ha Noi, Viet Nam*

[2]*Institute of Materials Science, Vietnam Academy of Science and Technology (VAST), 18 Hoang Quoc Viet, Cau Giay, Ha Noi, Viet Nam*

[3]*Graduate University of Science and Technology, VAST, 18 Hoang Quoc Viet, Cau Giay, Ha Noi, Viet Nam*

[*]Email: *tungnt@ims.vast.ac.vn*

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**Abstract.** THz metamaterial absorbers are often studied by computational techniques, where the influence of actual material parameters and fabricating limitation has not been completely understood. Here we present an experimental investigation on a far-infrared metamaterial absorber composed of a gold disk-shaped resonator, a silicon oxide spacer, and a gold film. The samples are fabricated using the UV laser lithography technique in combination with the electron-beam evaporation. The absorption feature of fabricated samples is examined by Fourier-transformed infrared spectroscopy and supported by finite integration simulations. By tuning the periodicity between meta unit-cell, it is demonstrated that the total absorptivity can be tuned up to 96 % at 58 THz. The finding results confirm earlier prediction on the unique absorption behavior of metamaterials in the THz regime.

*Keyword*: perfect absorbers, metamaterials, infrared spectroscopy.

*Classification numbers:* 2.1.2, 3.4.1.

## 1. INTRODUCTION

Light-matter interaction has been one of exciting phenomena that inspire material scientists to create novel functional materials for many years. In this context, metamaterials have been developed for independent manipulation of the electric and magnetic response through structural engineering [1, 2]. Since the debut in 2008, the novel concept of metamaterial absorbers (MMAs) has gained a huge attention for not only exciting fundamental knowledge but also the desire of using advanced materials in sensing, energy harvesting, and radiation probing based applications [3]. Basically, the interactions of light with a metamaterial medium can be generalized in terms of transmission T, reflection R. The absorption A can be defined as A = 1 – R - T, where A, R, and T are the functions of frequency. A simple strategy, which includes three functional layers, has been proposed for metamaterial absorbers to simultaneously eliminate the transmission and reflection. The first functional layer usually includes periodically-arrayed metallic resonators, which stay on the top of the second layer, a dielectric spacer [4]. Both metallic resonators and dielectric spacer are deposited on a ground metallic plane as the third layer. To vanish the reflection, the effective impedance of metallic resonators is matched to that of the free space through tuning the geometrical parameters of the top resonators. Meanwhile, the metallic ground plane is used as an electromagnetic shield to quench all incoming waves, finally turning out a zero transmission. The absorbed electromagnetic energy is commonly attributed to the dielectric loss generated by the induced coupling between the top metallic patterns and the bottom shield [5]. Since the last decade, the simplification of this strategy in fabrication and characterization makes it to be the most popularly used design for existing MMAs in literature so far [6 - 8].

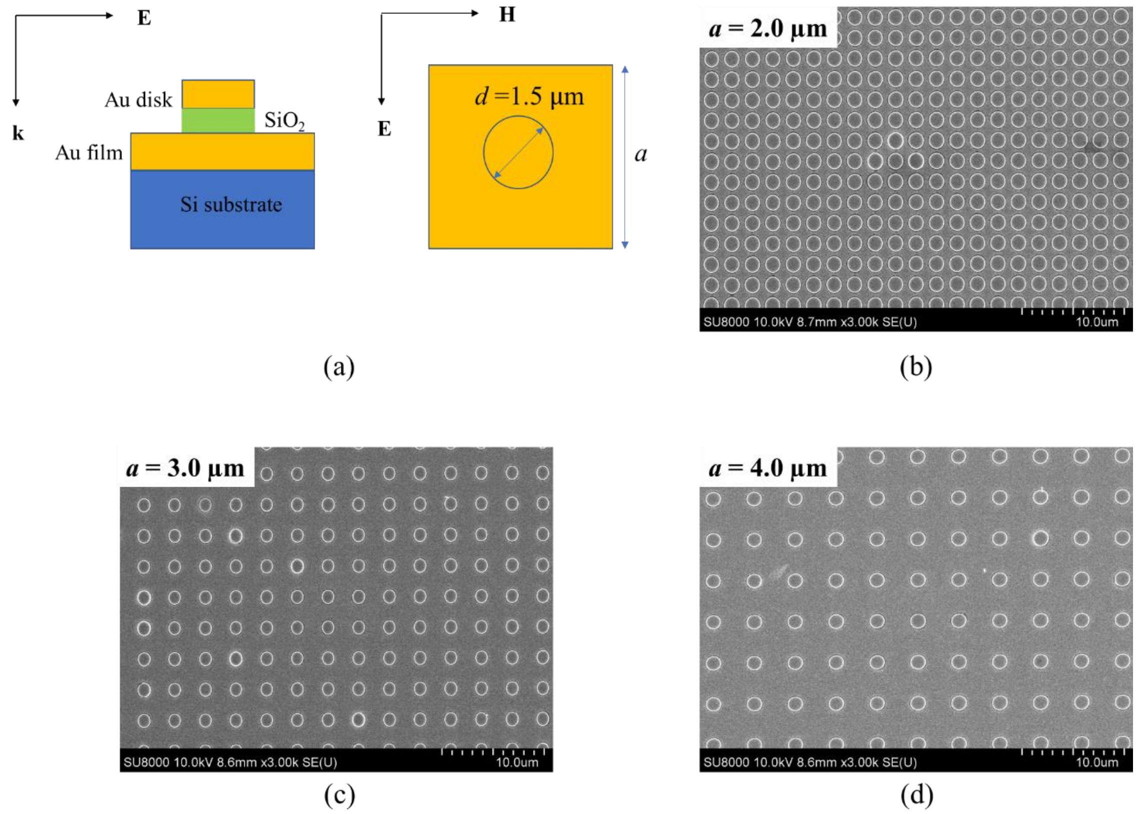


*Figure 1.* (a) The schematic drawing of a metamaterial unit cell. The structure is composed of a $SiO_2$ spacer sandwiched by a gold disk resonator and a gold film. (b-d) The SEM images of actual samples with a varied from 2.0 to 4.0 µm.

Among a wide variety of proposed structural designs, the disk-shaped metamaterial absorber has been investigated extensively due to its simplicity but high absorption efficiency [9 - 14]. The electromagnetic response of disk-shaped metamaterial absorbers at different wavelength, ranging from microwave to optical frequencies, has been studied. The size- and shape-dependence of the absorption intensity and frequency have been reported. Their sensitivity to ambient parameters and application potential have been also examined. Unfortunately, most of above mentioned works are computational and simulation-based while relevant experimental efforts, especially at THz frequencies, are very few due to the limitation of fabrication and characterization facilities in a compatible manner. Understanding the impact of material parameters and fabricating obstacles on electromagnetic response and actual performance of metamaterial absorber are still barriers to be overcome before they can be utilized in the real applications, for example, skin/tissue disease detectors [15], bolometers [16], THz modulators [17] and lenses [18]. In order to bridge this gap, we experimentally fabricate and characterize the absorption feature of a disk-shaped metamaterials operating at 60 THz. It is shown that an absorptivity of 97 % can be experimentally achieved, validating the computational prediction.

## 2. EXPERIMENTAL SETUP

A schematic drawing of the studied metamaterials unit cell with excitation source information is illustrated in Fig. 1(a). The structure consists of three functional layers. The top layer is an array of periodically arranged gold disk resonators while the bottom layer is a gold film. The middle layer is a disk spacer made of silicon dioxide. The thicknesses of gold patterns and film are 60 and 100 nm, respectively. The thickness of the dielectric spacer is 40 nm. The actual disk diameter is 1.65 ± 0.10 µm while the periodicity of the unit cell in the ***x***- and the ***y***-direction is varied to optimize the absorptivity.

The fabrication process is carried out as follows. Firstly, a 100-nm Au film is deposited onto a silicon substrate after a 5-nm Cr adhesive layer using the electron-beam evaporation. The direct-laser-writing technique (DL1000, Nano System Solutions) is applied to form the array of periodic disk-shaped patterns on the gold film surface. The final structure is then achieved after depositing $SiO_2$ and Au films and lifting-off the photoresist. During the fabrication process, the samples are held by a 350-µm Si substrate. Figure 1(b-d) show the scanning electron microscope (SEM) image of fabricated samples. The absorption feature of the fabricated samples is examined by a Fourier-transformed infrared spectrometer (FTIR 6300FV, Jasco). Due to the presence of the thick Au film, the transmittance T is completely quenched. The recorded reflection spectra R of the samples are used to determine the absorption A via the formula A = 1 - R. In order to support our experiments, the absorption and field distribution are calculated using the finite integration simulation technique embedded in CST Microwave Studio [19].

## 3. RESULTS AND DISCUSSION

Figure 2 presents the measured and simulated absorption spectra of the disk-shaped metamaterial absorbers with $a$ = 2.0, 3.0 and 4.0 µm. The dielectric permittivity of silicon dioxide materials is chosen as 1.95 for the studied frequency range [20]. The measured spectra are taken from 15 to 240 THz while the simulated ones are carried for a shorter range, from 25 to 100 THz, to minimize the computational workload. It can be seen that for the periodicity $a$ = 4 µm the disk-shaped metamaterial absorber exhibits an absorption peak at around 58 THz. The absorption intensity, however, is rather weak (about 43 %). While the underlying mechanism of the observed absorption peak will be discussed in the end of this section, we herein further examine the absorption behavior with different periodicities. When $a$ goes to 3 µm, the frequency of the absorption peak is unchanged but its strength is drastically enhanced from 43 % to 70 %. As demonstrated in Fig. 2, the disk-shaped metamaterial absorber has this tendency until $a$ = 2 µm, where the achieved absorption strength is up to 96 %.

Although the calculated absorption frequency is slightly deviated from the experimental value (65 and 58 THz, respectively), the simulated absorption feature in overall excellently reproduces the experimental one. When the periodicity becomes smaller, the absorption strength increases and increases up to 97 % at $a$ = 2 µm. The minor difference in the absorption frequency of simulated and measured results can be attributed to several reasons, including the imperfectness of the fabricated disk-shaped dimension and the spacer thickness, and/or the difference between the computational permittivity for $SiO_2$ and its actual frequency-dependent one.

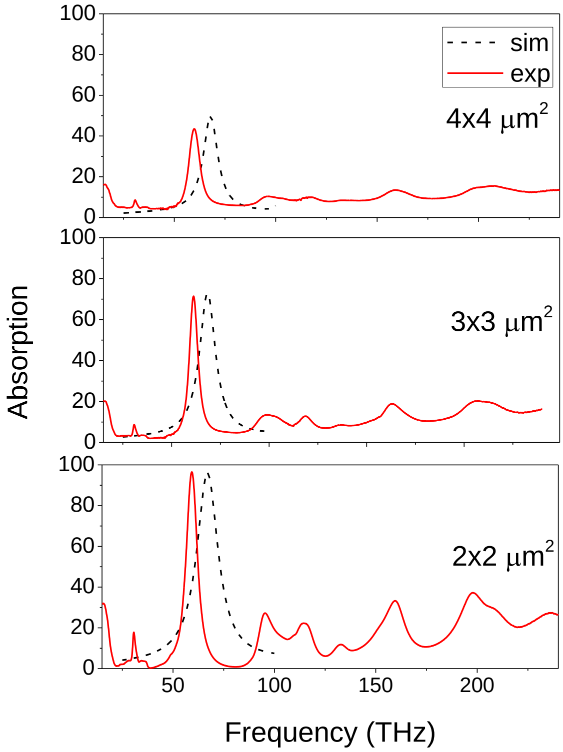


*Figure 2.* The absorption spectra of samples with a = 2, 3, and 4 μm measured by FTIR spectrometer and corresponding simulated results.

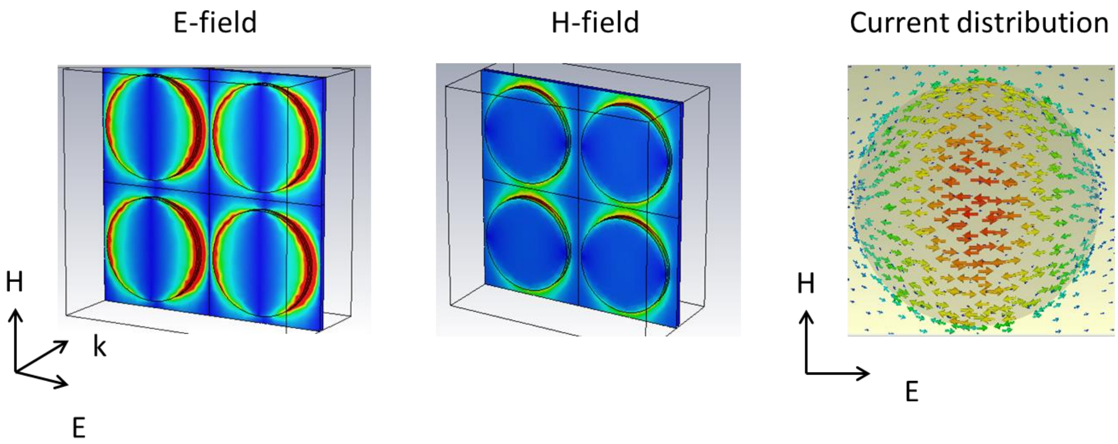


*Figure 3.* Calculated electric field, magnetic field and current distribution on the metal-dielectric interface at the absorption frequency. The field/current intensity is normalized between 0 (blue) and 1 (red). The arrow indicates the current direction.

Now if the absorption nature is associated with the magnetic resonance, the observed absorption behavior of the disk-shaped metamaterial in Fig. 2 can be explained as follow. Firstly, we estimate the absorption frequency by the magnetic resonant frequency using the formula $f \sim 1/d$, where $d$ is the disk diameter. Since the disk diameter is unchanged during the variation of the periodicity $a$, the absorption frequency should not be affected as observed. This explanation is agreed well with our experimental and simulated absorption spectra. While the absorption frequency is unaffected by the periodicity, the absorption strength reveals a different story. Reducing the periodicity in fact corresponds to an increase in the relative area ratio between the metallic pattern and the unit cell, or in the other words, an increase in the filling factor. The filling factors $F = \pi d^2/4a^2$ for $a$ = 4, 3, and 2 µm can be estimated as 0.13, 0.23, and 0.53, respectively. The relative intensity ratio at different periodicities normalized to the value at $a$ = 2 µm is calculated and compared with the relative ratio of the filling factor normalized to the value at $a$ = 2 µm as shown in Fig. 4. It can be seen that the increase of the absorption intensity can be qualitatively understood in terms of the filling factor. In particular, when $a$ goes from 4 to 2, the experimental and simulated absorption intensities behave similarly, showing a linear increase with an acceptable minor discrepancy. It is also witnessed an increasing trend for the relative ratio between filling factors when a reducing from 4 to 2. The increasing rate of the relative $F$ ratio for $a$ = 4 and 3 µm resembles that of the absorption intensity but suddenly increases for a = 2 µm, which might be related to a strong coupling between adjacent metallic disks at a short distance. Addressing the role of this mutual coupling in the absorption behavior of metamaterials certainly guarantees a particular interest for the future work towards the realization of THz metamaterial devices.

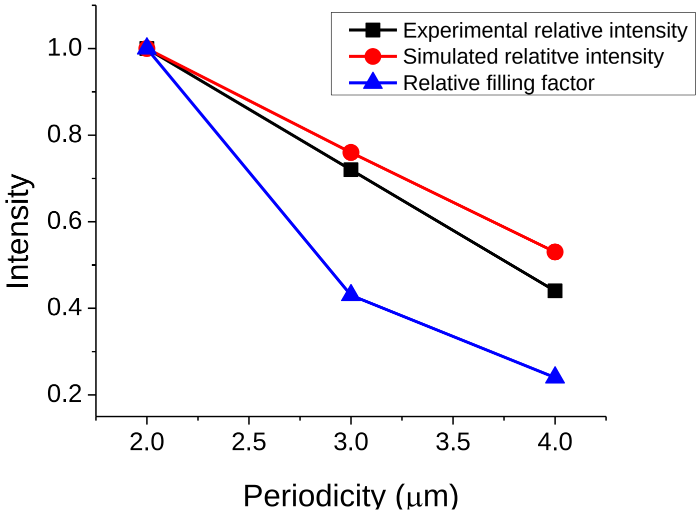


*Figure 4.* The relative intensity ratio at different periodicities normalized to the value at a = 2 µm is calculated and compared with the relative ration of the filling factor normalized to the value at a = 2 µm.

## 4. CONCLUSIONS

In summary, the absorption feature of a disk-shaped metamaterials and the effect of the periodicity were experimentally and computationally studied. The absorption spectra of the metamaterials were measured by the FTIR spectrometer and simulated by the finite integration technique. The induced electric field, magnetic field, and current distribution were computed to visualized the absorption mechanism. It can be experimentally concluded that the disk diameter responds for the absorption frequency while the filling factor governs the absorption strength. The experimental observation was strongly supported by the numerical ones. Our finding results can be served as an important information to verify the understanding of metamaterial absorbers proposed by earlier simulated works.

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***CRediT authorship contribution statement.*** N.T.T: Design the simulations and experiments, Perform the experiments, Supervision, Manuscript writing. L.H.P: Perform the simulations, Data analysis, Manuscript writing.

***Declaration of competing interest.*** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## REFERENCES

1. Veselago V. G. - The electrodynamics of substances with simultaneously negative values of $\varepsilon$ and $\mu$, Sov. Phys. Usp. **10** (1968) 509.
2. Pendry J. B. - Light runs backwards in time, Phys. World **13** (2000) 27.
3. Landy N. I., Sajuyigbe S., Mock J. J., Smith D. R., and Padilla W. J. - Perfect Metamaterial Absorber, Phys. Rev. Lett. **100** (2008) 207402.
4. Tao H., Bingham C. M., Strikwerda A. C., Pilon D., Shrekenhamer D., Landy N. I., Fan K., Zhang X., Padilla W. J., and Averitt R. D. - Highly flexible wide angle of incidence terahertz metamaterial absorber: Design, fabrication, and characterization, Phys. Rev. B **78** (2008) 241103.
5. Zhang Y., Feng Y., Zhu B., Zhao J., and Jiang T. - Graphene based tunable metamaterial absorber and polarization modulation in terahertz frequency, Opt. Express **22** (2014) 22743.
6. Watts C. M., Liu X., and Padilla W. J. - Metamaterial Electromagnetic Wave Absorbers, Adv. Mat. **24** (23) (2012) OP98 - OP120.
7. Viet D. T., Hien N. T., Tuong P. V., Minh N. Q., Trang P. T., Le L. N., Lee Y. P., and Lam V. D. - Perfect absorber metamaterials: peak, multi-peak and broadband absorption, Opt. Comm. **322** (2014) 209.
8. Ishikawa A. and Tanaka T. - Metamaterial Absorbers for Infrared Detection of Molecular Self-Assembled Monolayers, Sci. Rep. **5** (2015) 12570.
9. Tsai C. Y., Lu S. P., Lin J. W., and Lee P. T. - High sensitivity plasmonic index sensor using slablike gold nanoring arrays, Appl. Phys. Lett. **98** (2011) 153108.
10. Cheng C. W., Abbas M. N., Chiu C. W., Lai K. T., Shih M. H., and Chang Y. C. - Wide-angle polarization independent infrared broadband absorbers based on metallic multi-sized disk arrays, Opt. Express **20** (2012) 10376.
11. Guddala S., Kumar R., and Ramakrishna S. A. - Thermally induced nonlinear optical absorption in metamaterial perfect absorbers, Appl. Phys. Lett. **106** (2015) 111901.

12. Khan A. D., Amin M., Ali A., Khan S. D., and Khan R. U. - Multiple higher-order Fano resonances in plasmonic hollow cylindrical nanodimer, Appl. Phys. A **120** (2015) 641.
13. Wang Q., Han W., Liu P., and Dong L. - Electrically Tunable Quasi-3-D Mushroom Plasmonic Crystal, J. Lightwave Tech. **34** (2016) 2175.
14. Jahangiri P., Zarrabi F. B., Moghadasi M. N., Arezoomand A. S., and Heydari S. - Hollow plasmonic high Q-factor absorber for bio-sensing in mid-infrared application, Opt. Comm. **394** (2017) 80.
15. Choudhury B., Thiruveni B., Reddy P. V., Jha R. M. - Soft Computing for Terahertz Metamaterial Absorber Design for Biomedical Application, Computers, Materials and Continua. **37** (2013) 135.
16. Strikwerda A. C., Tao H., Kadlec E. A., Fan K., Padilla W. J., Averitt R. D., Shaner E. A., Zhang X. - Emerging Trends in Terahertz Metamaterial Applications, Proceedings of 36th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz) (2011) pp. 1-2.
17. Sheng L. J. and Jun L. J. - A novel terahertz wave switch based on metamaterial, Microwave And Optical Technology Letters **53** (2011) 276.
18. Neu J., Krolla B., Paul O., Reinhard B., Beigang R., Rahm M. - Metamaterial-based gradient index lens with strong focusing in the THz frequency range, Opt. Express **18** (2010) 27748.
19. www.cst.com, (accessed 21 May 2020).
20. Tan C. Z. - Determination of refractive index of silica glass for infrared wavelengths by IR spectroscopy, J. Non-Crys. Solids **223** (1998) 158.
21. Bui X. K., Bui S. T., Tung N. T., Hien N. T., Kim Y. J., Chen L. Y., Lee Y. P., Pham T. L., Lam V. D. - Realization for dual-band high-order perfect absorption based on metamaterial, J. Phys. D: Appl. Phys. **53** (2020) 105502.
22. Thuy U. T. D., Thuy N. T., Tung N. T., Janssens E., and Liem N. Q. - Large-area cost-effective lithography-free infrared metasurface absorbers for molecular detection, APL Materials **7** (2019) 071102.
23. Zhou J., Economon E. N., Koschny T., and Soukoulis C. M. - Unifying approach to left-handed material design, Opt. Lett. **31** (2006) 3620.