Epsilon-near-zero Metal-slit Array Antenna with Holes

Tatsuya Sato[1], Nozomu Koja[1], Takehito Suzuki[1*]

[1]Major in Electrical and Electronic Engineering, The Graduate School of Science and Engineering, Ibaraki University, 4-12-1 Nakanarusawa, Hitachi, Ibaraki 316-8511, Japan Email: takehito@mx.ibaraki.ac.jp

***Abstract*—Metamaterials offer unprecedented refractive indices and have a strong potential for evolving into metadevices with on-demand electromagnetic properties today. However, it has yet to be fully understood how an epsilon-near-zero (ENZ) structure can open up the potential of terahertz metadevices with the expected extraordinary performance. We show that an ENZ metal-slit array antenna with holes can manipulate terahertz waves as observed by a terahertz camera. The ENZ structure may provide the potential for developing attractive applications in the terahertz waveband.**

I. Introduction and Background

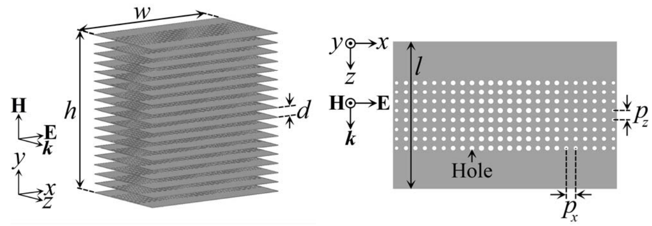
Metamaterials offer the potential to move beyond the limitations of refractive indices in naturally available compounds and may offer the potential to make the development of hitherto unavailable man-made media possible. Such man-made electromagnetic media could provide a paradigm shift in the control of electromagnetic waves, and rapidly evolve beyond the basic metamaterial structures into metadevices with on-demand electromagnetic properties [1]. However, it remains to be shown how three-dimensional ENZ structures [2, 3] can enable attractive applications in the terahertz waveband. Here, inspired by the ENZ concept, we show that a metal-slit array antenna with holes can generate gradient indices of $0<n_{\mathrm{eff}}<1$ and manipulate terahertz waves.

II. Mechanism

Fig. 1 shows a schematic of an ENZ metal-slit array antenna with holes. Holes in the metal with different radii on the metal plates control the effective refractive index in the range $\sqrt{1-(\lambda/2d)^2} \le n_{\mathrm{eff}} < 1$, where λ is the wavelength in free space and d is the slit distance. A design where the refractive index approaches 0 from the center to the periphery on the input face of the antenna produces a focusing effect arising from the $0<n_{\mathrm{eff}}<1$ gradient indices. The effective refractive index approaches 1 with larger radii because the free space in the metal slit increases. The radii of the holes in the antenna become smaller from the center to the periphery in the x-y plane and are the same dimensions in the direction of propagation (z).

III. Antenna Design

A periodic analysis calculates the guide wavelength and derives the effective refractive index in the design of the dimensions of the holes. A periodic model with multiple holes of the same radii is extracted from the full model assuming periodic boundary walls at the vertical and horizontal directions of the metal-slit array. Fig. 2 shows the relation between the radius of a hole and an effective refractive index at 0.5 THz which is derived by a guide wavelength calculated using periodic analysis. The design frequency is 0.5 THz, with the slit distance d, the hole pitch p_x, p_z, and the propagation length l set to d =350 μm, $p_x = p_z$ = 250 μm, and l =2.0 mm, respectively.



(a) (b)

Fig. 1 (a) Schematic of the metal-slit array antenna with gradient indices of $0<n_{\mathrm{eff}}<1$ controlled by metal holes. (b) Surface of a metal plate with holes.

Fig.3 shows a map of gradient indices in the metal-slit array antenna, and Table 2 lists the gradient indices. The effective refractive indices are discretely distributed because the effective refractive index is uniform in an area determined by the slit distance d and the hole pitch p_x. The antenna is divided into 24 areas along the vertical (y) direction and is divided into 17 areas along the horizontal (x) direction. As shown in Fig. 3, the distribution of gradient indices is symmetric with respect to the x- and y-axes, and there are 108 different values in the 408 cells. The gradient indices are determined by the distance from the center on the input face of the antenna, corresponding to all optical lengths at a focusing point. The dimensions of the holes are designed using the relation between a radius of a hole and an effective refractive index in Fig. 2 after determining the distribution of refractive indices. The minimum radius of a hole in the metal slit is 55 μm with n_{eff} =0.55 and the maximum is 100 μm with n_{eff} =0.71. Table 2 lists the parameters of the metal-slit array antenna with a design frequency of 0.5 THz according to the optimized design.

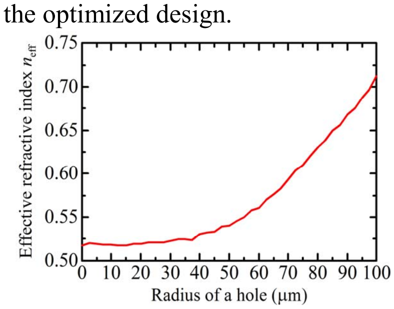


Fig. 2 Relation between the radius of a hole and an effective refractive index at 0.5 THz.

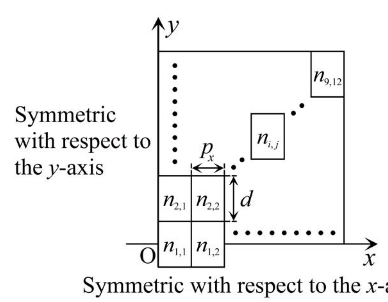


Fig. 3 Distribution of gradient indices in the metal-slit array antenna.

Table 1 Gradient indices

$n_{1,1}$	0.7108	$n_{1,2}$	0.7098	$n_{2,1}$	0.7097	$n_{2,2}$	0.7087	•••	$n_{9,12}$	0.5698

IV. Measurements

Fig. 4 shows the fabricated ENZ metal-slit array antenna with holes. The holes are accurately fabricated by etching with very small fabrication errors. The metal plates of a fabricated antenna are coated with gold to reduce conductor losses. Fig. 5 and Fig. 6 show the cross section of the electric field distribution and radiation pattern at 13.0 mm from the front of the antenna as observed by a terahertz camera. The radiation patterns along the vertical (y) direction of the metal-slit array are narrower than those along the horizontal (x) direction, and the changes in the measurements coincide with the simulation. The interference fringes in the vertical direction of the metal-slit array would be caused by diffraction from the base.

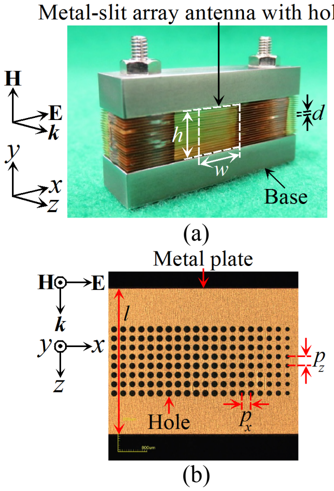


Fig. 4 (a) Photograph of the fabricated metal-slit array antenna with gradient indices of $0<n_{eff}<1$ controlled by metal holes. (b) Surface of a metal plate with holes.

Table 2 Antenna parameters at the design frequency of 0.5 THz.

d	350 μm	p_x	250 μm	Number of plates	18
h	6.31 mm	p_z	250 μm		
w	6.0 mm	Thickness of the plate	20 μm		
l	4.0 mm				

V. Summary

We show that an ENZ metal-slit array antenna with low losses and good robustness can focus and control a terahertz wave. The ENZ structure potentially offers a wide range of applications, including high directivity antennas, beam dividers, beam steering elements, phase control devices, and novel filters.

Acknowledgments

This research has been supported by a Grant-in-Aid for Young Scientists (A) (No. 26706017) from the Japan Society for the Promotion of Science (JSPS), a Grant-in-Aid for Challenging Exploratory Research (No. 26600108) from Japan Society for the Promotion of Science (JSPS), and a "Super Highway" the accelerated research to bridge university IPs and practical use (No. SHW005) from the Japan Science and Technology Agency (JST).

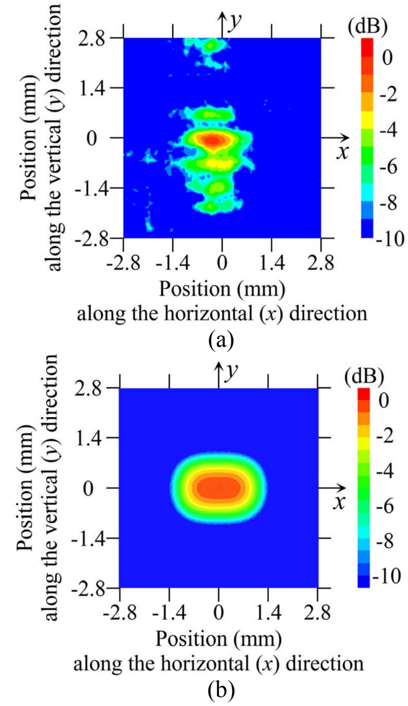


Fig. 5 Cross sections of the electric field distribution 13.0 mm from the antenna at 0.48THz (a) measured and (b) HFSS simulation.

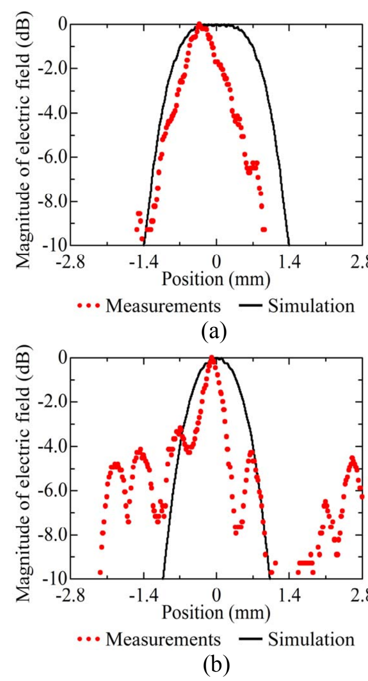


Fig. 6 Radiation patterns at 0.48 THz along the (a) horizontal (x) direction and (b) vertical (y) direction.

References

[1] N. I. Zheludev et al., "From metamaterials to metadevices," *Nature Mater.*, vol. 11, no. 11, pp. 917-924, Nov. 2012.

[2] T. Suzuki et al., "Parallel plate lens with metal hole array for terahertz wave band," *Appl. Phys. A*, vol. 115, no. 2, pp. 403-408, May 2014.

[3] V. Torres et al., "Experimental Demonstration of a Millimeter-Wave Metallic ENZ Lens Based on the Energy Squeezing Principle," *IEEE Trans. Antennas Propag.*, vol. 63, no. 1, pp. 231-239, Jan. 2015.