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Experimental verification of nonreciprocal electromagnetic metasurface in a finite-size array

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This paper presents experimental verification results for a finite-sized array of a simple non-reciprocal metasurface elements. The metasurface elements consists of ferrite loaded metal patches. Experimental results demonstrate nonreciprocity, achieving isolation exceeding 20 dB at 6.4 GHz in a 2×2 array. Additionally, these findings are compared with simulation results for a 4×4 array to validate its practicality in a finite array setting.

Introduction: Controlling the absorption, reflection, and propagation of radio waves is crucial for optimizing their utilization in many applications. Various methods, including the use of metamaterials and metasurfaces, have been explored to manipulate radio wave characteristics [1, 2]. In recent years, there has been a surge in research on nonreciprocity-related metasurfaces as a novel approach to space-based radio wave control [3–5], addressing the need for both symmetric and spatially asymmetric functions [6, 7]. Nonreciprocal metasurface technology has the potential for beneficial applications in electromagnetic interference protection, electromagnetic security enhancement, and radio stealth. As the demand for diverse controls increases, the complexity of patch shapes and processing methods grows, potentially compromising functional redundancy and structural strength. With the escalating power of radio waves, high voltage resistance emerges as a pivotal element in radio wave metamaterials. Balancing these factors is challenging, emphasizing the importance of achieving complex functions with a simple structure.

The research direction is focused on achieving a non-reciprocal metasurface featuring a power-resistant structure devoid of electronic circuits or intricate designs to accommodate variations in radio wave output and operational range. Our research group has proposed a method to implement a non-reciprocal metasurface using a straightforward combination of cylindrical ferrite and metal patches [8]. Previous reports focused on theoretical proposals on an infinite plane, electromagnetic field simulations, and experimental results on unit cells [9]. In this report, we present experimental verification results for finite-sized arrays, addressing these critical issues.

Proposed structure: After characterizing the infinite plane, efforts are made to ascertain if these properties persist in the finite plane. Design activities are conducted using CST Studio Suite, with CST F-solver's unit cell analysis employed for the infinite plane. The proposed structure's unit cell, assuming vertical polarization, comprises a cylindrical ferrite at the center and a metal patch on one side, maintaining the aspect ratio akin to a waveguide. This design, elucidated in Figure 1, achieves nonreciprocity through the combination of a cylindrical ferrite array and a metal patch array.

As depicted in the upper segment of Figure 1, upon applying a magnetic field parallel to the ferrite's height direction, the ferrite rotates while propagating. The arrayed cylindrical ferrite exhibits nearly complete transmission across the analysis frequency band. However, within the operational frequency band of 6.3 to 6.5 GHz, corresponding to the ferrite diameter, minor reflection and absorption characteristics are observed. The relationship between the ferrite diameter R_f and the operating center frequency f_0 is determined by Equation (1), akin to general circulator design, albeit with potential roughness compared to circulator designs requiring phase matching of right and left rotation [10].

$$R_f = \frac{1.84}{2\pi f_0 \sqrt{\mu_r \varepsilon_r}} \tag{1}$$

Here, μ_r denotes relative permeability of the ferrite, and ε_r signifies relative dielectric constant of the ferrite. For this study, various ferrite characteristics are assumed based on commercially available C-band circulators equivalent to G-1600 [11], with a standardized diameter of 7 mm. Additionally, the ferrite height is set at 1 mm, though it can be adjusted via multilayering. As depicted in the middle row of Figure 1, the metal patch array covers half of the unit cell excluding the ferrite diameter, featuring an array structure resembling a one-dimensional slit shape connected longitudinally. This configuration functions as a bandpass filter, demonstrating transmission characteristics from 6 to 8 GHz. When combined with the ferrite array, the metal patch array predominantly affects one side due to the swirling propagation characteristics of the ferrite. Consequently, as illustrated in the lower portion of Figure 1, within the ferrite's resonance range of 6.3 to 6.5 GHz, S_{21} exhibits characteristics akin to the metal patch array alone, with only S_{12} demonstrating non-reciprocity resulting in reduced transmittance.

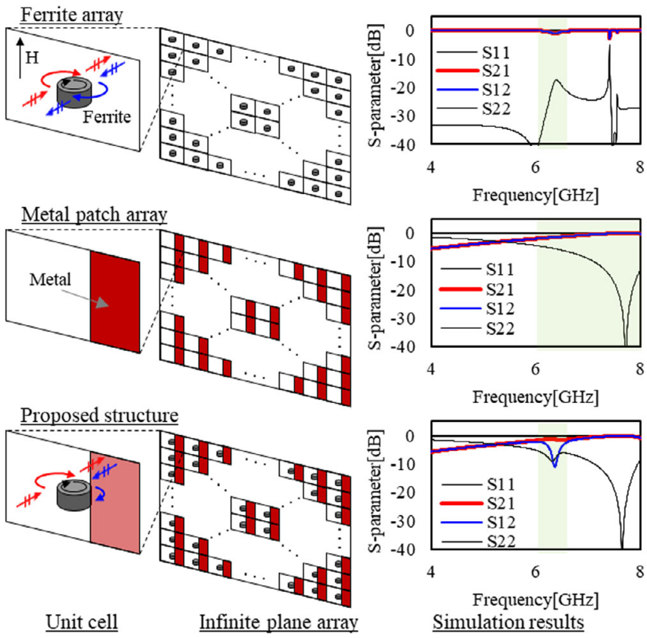

Fig. 1 *Proposed nonreciprocal metasurface concept*

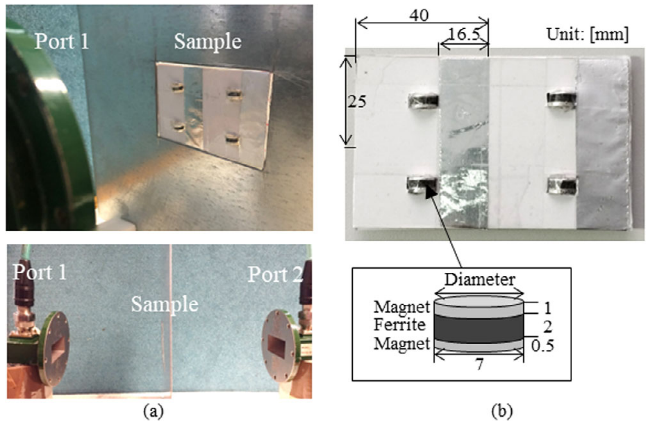

Fig. 2 *Experimental setup (a) and 2×2 array sample (b)*

Given that the rotation direction of the proposed structure varies based on magnetization direction, enhanced controllability is anticipated through electromagnet utilization for magnetization and manipulation of the metal patch array's shape.

Characteristics of finite structure: The primary aim of this study is to demonstrate the effects of a finite-sized array with practical implications. As depicted in Figure 2, verification results of a 2 × 2 finite array are presented. Furthermore, Figure 3 illustrates the utilization of the same 2 × 2 model to validate agreement with experimental values, which, upon ensuring simulation accuracy, is expanded to a 4 × 4 array. Consequently, it is demonstrated that even with an increased number of finite arrays, equivalent characteristics to those of an infinite plane can be achieved.

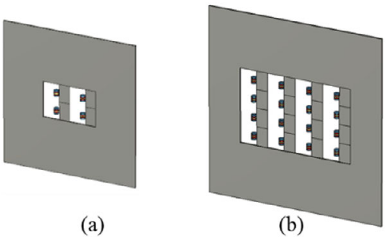

Fig. 3 *Simulation model, 2×2 (a) and 4×4 (b)*

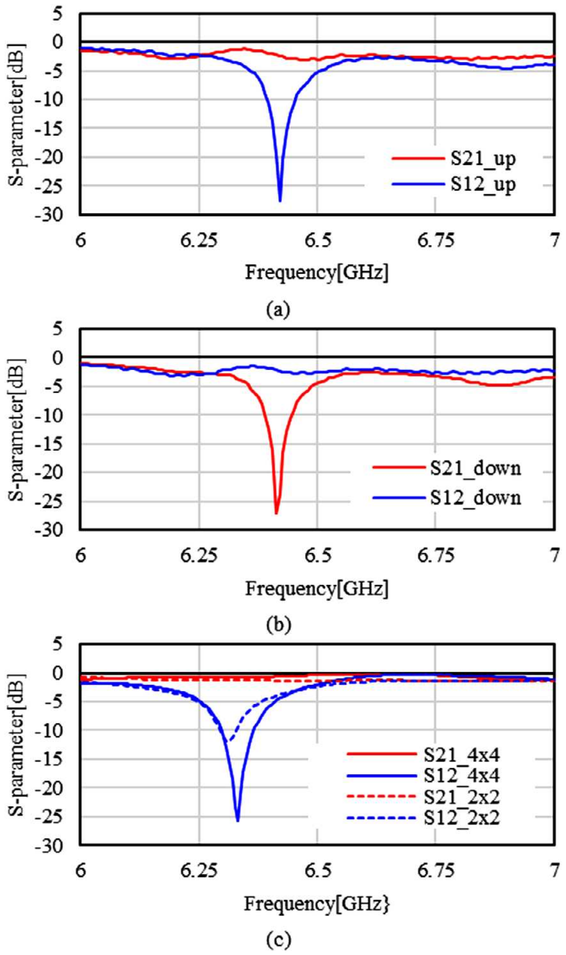

Fig. 4 *Experimental results with changing the direction of the magnetic field. Upward magnetic field (a) and downward magnetic field (b), and simulation results for comparison (c)*

The unit cell dimensions used for experimentation and simulation remain consistent with the infinite plane analysis, featuring a width of 40 mm, height of 25 mm, ferrite diameter of 7 mm, and a two-layer ferrite height of 2 mm. The array substrate consists of 0.8 mm cardboard material, with the ferrite protrusion being thin. Additionally, as depicted in the experimental setup in Figure 2, a sample containing a metal plate fixture for diffraction blocking is positioned between the radiation source pair and measured using a vector network analyser (Agilent E8562B). A similar metal plate fixture for diffraction blocking is arranged similarly in the simulation.

Experimental results: Experimental results (Figure 4a) confirm non-reciprocity with an isolation level of 20 dB or higher near 6.3 GHz. At this juncture, the bandwidth extends to 50 MHz, wherein isolation of 10 dB or more is achieved, and the transmission of S_{21} within the band exceeds −3 dB. Additionally, Figure 4b demonstrates correct inversion of S_{21} and S_{12} upon altering the magnetic field direction from upward to downward. Furthermore, both the 2 × 2 and 4 × 4 arrays exhibit pronounced resonance around 6.3 GHz, as evidenced by Figure 4c.

Finally, Figure 5 illustrates simulation results indicating the optimization of ferrite height from 1 to 8 mm. Increasing ferrite height enlarges

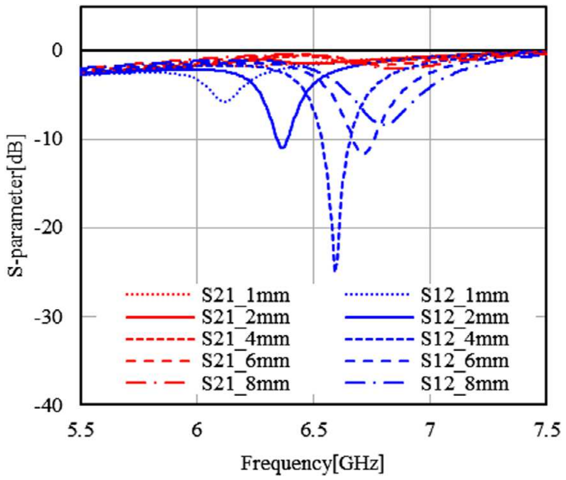

Fig. 5 *Simulation results with changing the height of the ferrite*

the resonance peak and elevates the frequency. However, if the ferrite height exceeds one-third of the unit cell height, non-reciprocity plateaus. Balancing ferrite quantity per unit cell accounts for overall weight and cost, necessitating bandwidth optimization. These findings affirm the functionality of the proposed non-reciprocal metasurface structure as a finite array, employing solely cylindrical ferrite and metal patches.

Conclusion: This paper reports experimental results on the characteristics of a simple metasurface structure using ferrite in a finite array, aiming to achieve a non-reciprocal metasurface with high redundancy. The experiment verified non-reciprocity with an isolation amount exceeding 20 dB at the design frequency of 6.4 GHz with a 2 × 2 finite array. The proposed structure holds potential for expansion, such as band widening by adjusting ferrite size, control through magnetization methods, and shaping the metal patch array. Ongoing research will address issues related to these directions.

Author contributions: **Kazuhiro Takahagi**: Conceptualization; methodology; formal analysis; data curation; investigation; writing—original draft; visualization. **Alan Tennant**: Supervision; project administration; funding acquisition; resources; software; writing—review & editing.

Conflict of interest statement: The authors declare no conflicts of interest.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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