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LETTER

Experimental validation of nonreciprocal metasurface using simple structure

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Abstract

The non-reciprocity of electromagnetic waves is a technology garnering significant attention for its applications in electromagnetic security and the mitigation of electromagnetic interference, serving to control radio waves in space. This article outlines a comprehensive design approach for a novel non-reciprocal structure that integrates ferrite and metal patches. Additionally, it presents experimental results utilizing two types of ferrites. The experiments demonstrated the attainment of 15 dB isolation at both 6.25 GHz and 6.5 GHz.

1 | INTRODUCTION

Recently, there has been extensive research on the potential of metasurfaces in the radio wave domain. They are not only employed as a surface processing technology but have also been utilized to develop additional antenna functionalities [1]. On the other hand, the application field for plane wave radio waves is limited to controlling functions like reflection, transmission, and absorption. These controls are associated with plane wave parameters, known as frequency selection, energy selection etc. [2–4]. This article focuses on the distinction in radio waves based on their direction. These technologies, referred to as one-way mirrors, are commonly employed in electronic circuits using directional couplers and isolators, yet there are limited reports of their implementation as planar devices. These technologies are valuable for achieving stealth and electromagnetic security and exhibit potential uses as amplifiers and oscillation sources, such as in laser oscillation. The technology referred to as non-reciprocal plane or one-way mirror can be broadly categorized into two types: one that provides non-reciprocity for reflection at an interface [5] and another that offers non-reciprocity for transmission [6]. In this article, we focus on the latter, the transparent type, for its suitability in stealth technology. There is a research report in which a transparent non-reciprocal metasurface was realized by combining an antenna and an electronic circuit element [7], but it relies not only on antenna characteristics but also on delicate adjustments of the element characteristics. The structure we propose is a simple one that can achieve non-reciprocity without the need for complex adjustments [8].

This article presents a theoretical design method and experimental results for an array plane with a straightforward unit cell structure that combines cylindrical ferrite and metal foil.

2 | NONRECIPROCAL METASUFACE STRUCTURE

2.1 | Proposed structure

To achieve non-reciprocal control of transmission and reflection for plane waves, it is necessary to capture incoming radio waves, discern their orientation, and selectively reflect or transmit them. In our research group, we focus on cylindrical ferrite, commonly employed in circulators and related devices. Cylindrical ferrite exhibits a unique property, where radio waves with vertical polarization, a polarization orthogonal to the height of the cylinder, undergo circular propagation along the cylinder's diameter when subjected to a magnetic field applied parallel to the cylinder's height. This phenomenon, as expressed in (1) [9], is due to the anisotropy of permeability μ in ferrite under the influence of the applied magnetic field. Depending on the direction of the magnetic field, it exhibits either clockwise or counterclockwise characteristics, as depicted in Figure 1a,

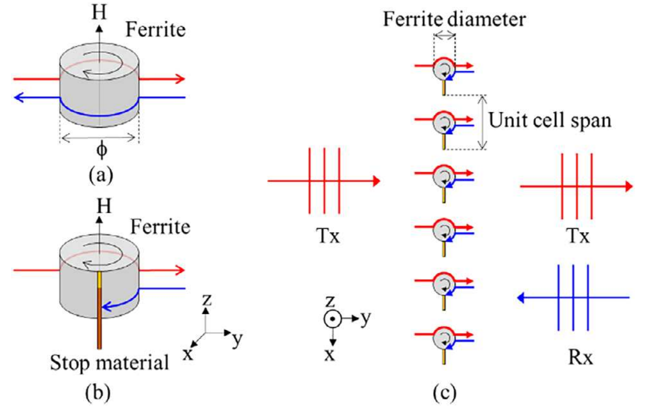

FIGURE 1 Operating principle of the proposed structure; the state of propagation in cylindrical ferrite (a), nonreciprocal structure (b), and array structure (c).

$$[\mu] = \begin{bmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix}. \tag{1}$$

Here, μ represents relative permittivity, μ_0 is the permeability in vacuum, and κ is the imaginary part of the permeability. This property enables radio waves passing through the vicinity of the ferrite to localize on either the left or right side of the ferrite. By introducing metallic patches as blocking elements on one side of the ferrite, as illustrated in Figure 1b, we create a structure that exhibits non-reciprocity for the same radio wave. This cylindrical ferrite and metallic patch configuration, arranged as unit cells, is shown in Figure 1c. As depicted in Figure 1c, the determination of unit cell spacing and ferrite diameter is contingent upon the operational frequency band.

In this study, we focus on the C-band, specifically the 6 GHz range, due to its utility in electromagnetic interference mitigation and stealth measures, as well as the ease of experimental verification. The unit cell spacing, optimized through simulations with reference to the cutoff frequency as a waveguide, is set at 40 mm width and 25 mm height. The diameter of the ferrite is determined using (2) to calculate the circulator's diameter [10].

$$R = \frac{1.84\lambda}{2\pi\sqrt{\mu\varepsilon}}, \tag{2}$$

where, λ is the wavelength, μ is the effective permeability of the ferrite material, and ε is the dielectric constant of the ferrite material. In contrast to a circulator, this structure does not necessitate the phasing of right and left rotations. Therefore, we will optimize it, including diameter reduction.

2.2 | Array structure simulation

To analyze the characteristics of the proposed structure, we employed CST's F-solver unit cell analysis to investigate the properties of an infinite plane. The non-reciprocal frequency characteristics are contingent on the material parameters of the ferrite and the dimensions within the unit cell. In this simulation, we set the ferrite to have ideal properties, operating in the microwave band with a dielectric constant of 15, a permeability of 1.1, a saturation magnetization of 2800 Gauss, and an applied magnetic field of 1270 Gauss. Figure 2a illustrates the dimensions, with a height of 25 mm, a width of 45 mm, and a ferrite diameter of 7 mm. For cylindrical ferrite, optimal non-reciprocity is achieved when the height matches the unit cell height. However, to apply a magnetic field, it is necessary to place magnets above and below, so the height is set to 22 mm. Figure 2b presents the simulation results for the infinite plane using the defined unit cell, with the upper part showing results with ferrite and the lower part without ferrite. From this figure,

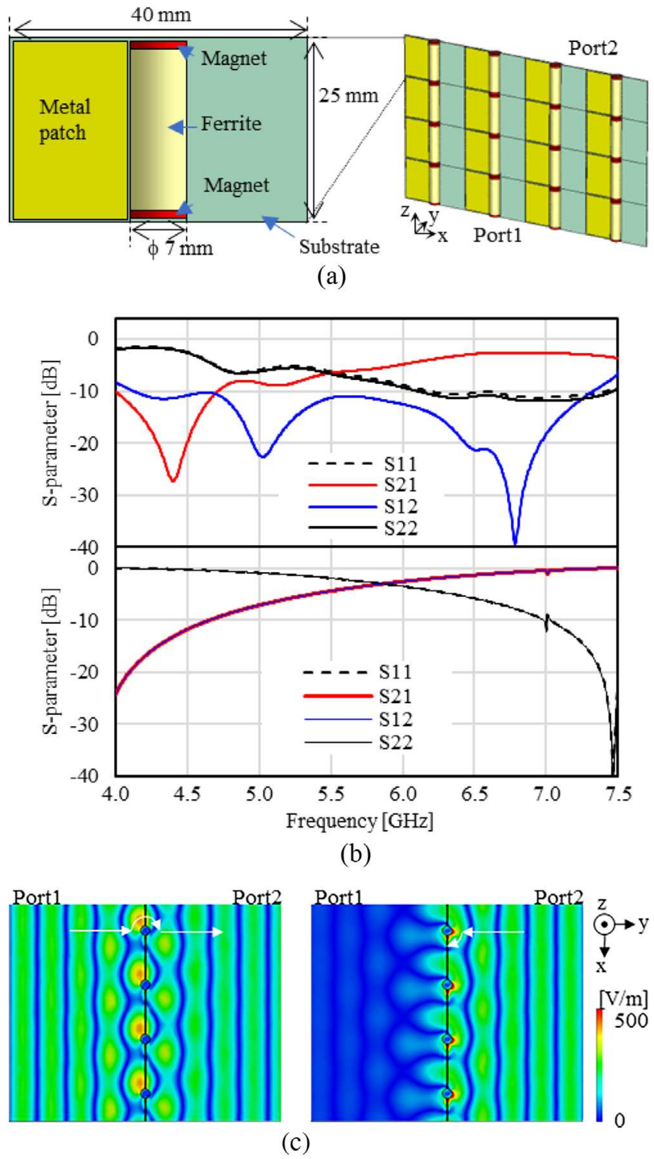

FIGURE 2 Schematic diagram of unit cell structure and infinite plane array (a), S-parameter results with ferrite and without ferrite (b) and electric field distribution diagram (c).

it can be seen that the nonreciprocal S_{21} and S_{12} parameters are separated over a broad band from 5 GHz to 7 GHz. The S_{21}, which propagates toward the metal patch side, exhibits characteristics similar to those without ferrite, confirming that the metal patch array properties are accurately obtained. On the other hand, the S_{12} propagates towards the gap side due to the ferrite's rotational properties, operating as a stopband in the reverse direction. As a result, the reflection coefficients S_{11} and S_{22}, which reflect the amount of reflection, reached −10 dB in the 6–7 GHz range, and the isolation, indicating nonreciprocity, reached a maximum of 30 dB or more. The electric field distribution at 7 GHz is depicted in Figure 2c, revealing that the left figure for incident from port 1 signifies transmission propagation, while the right figure for incident from port 2 indicates blockage. These results exhibit a distribution akin to the rotational propagation characteristic shown in Figure 1c, affirming the theoretical functionality of the proposed structure.

These nonreciprocal characteristics depend on the metal patch array size, ferrite material properties, and ferrite size. The ferrite diameter is defined by (2), and the patch array is specified as shown in Figure 2b. The ferrite material properties require the optimal selection of permeability and applied magnetic field strength corresponding to the saturation magnetization. Although the permeability of ferrite is close to 1 at high frequencies, it can take higher values depending on the material. Figure 3a shows the results of varying the parameters between 1 and 2. As a result, it was confirmed that the nonreciprocity peak shifts to the lower frequency side as the permeability increases. Next is the ferrite height. Ideally, the ferrite height should match the unit cell height to obtain rotational propagation characteristics, but it becomes finite in consideration of the placement of magnets for magnetization and the realization of a parallel magnetic field. Figure 3b shows the results of varying the height between 22 mm and 19 mm. From these results, it is understood that as the ferrite height decreases, the isolation decreases, and the bandwidth narrows. Finally, the applied magnetic field is taken as a parameter. The applied magnetic field is lower than the saturation magnetization, typically being about half of it. Figure 3c shows the results of varying the magnetic field from 1000 Gauss to 1500 Gauss. As a result, it was found that the nonreciprocity shifts to the higher frequency side as the applied magnetic field increases. By optimizing these parameters, nonreciprocity can be controlled.

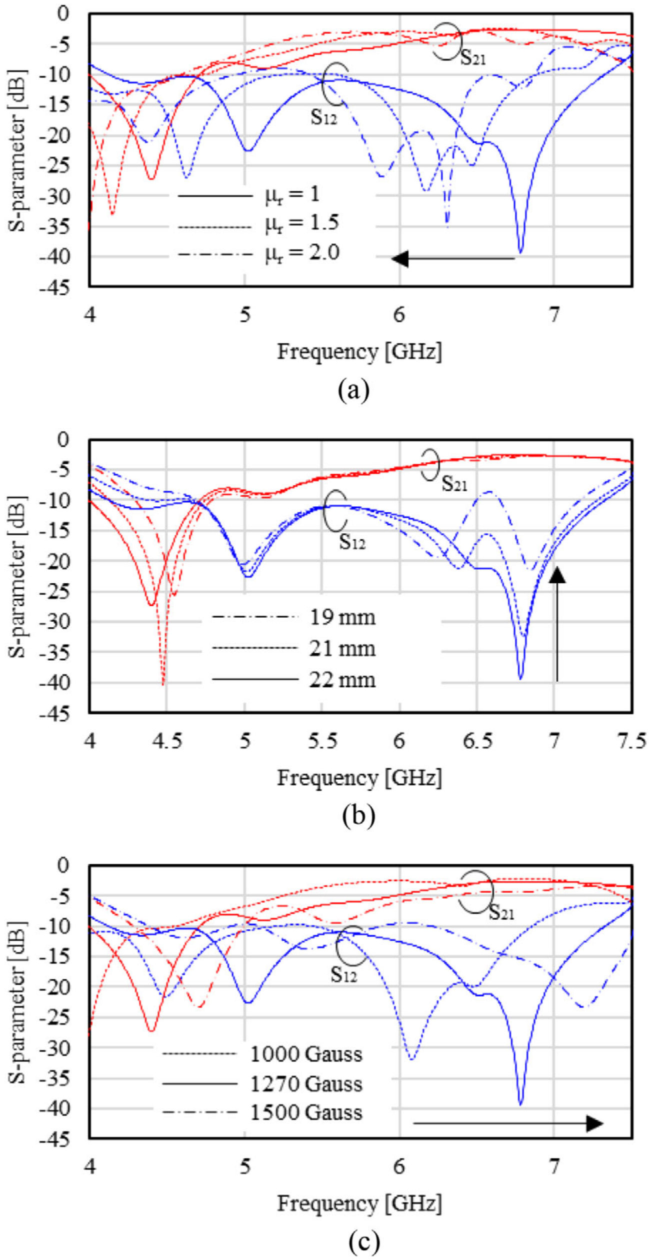

FIGURE 3 S-parameters for variations in each characteristic: (a) change in magnetic permeability, (b) change in height, and (c) change in applied magnetic field.

3 | EXPERIMENT

The experiment employed two types of commercially available ferrite circulators for comparative verification. Sample A corresponds to the ferrite used in the first C-band circulator manufactured by Molex, while Sample B is the ferrite used in another C-band circulator manufactured by Skyworks. Both ferrites have a thickness of 1 mm, but as depicted in Figure 4b,c, Sample A is magnetized from the top and bottom of the ferrite using magnets, while Sample B is designed with the magnetic field applied only from above. Furthermore, their respective ferrite diameters are 7 mm and 4 mm.

In the experimental results, illustrated in Figure 5, Sample A achieved an isolation of −15 dB near 6.5 GHz, while Sample B attained an isolation of −15 dB around 6.25 GHz. Moreover, we observed a property in which the blocking direction reversed when the magnetic field was reversed, confirming proper non-reciprocity. To estimate the ferrite properties from the experimental results, a back-fit simulation was conducted, replicating the structure used in the experiment. The results showed that the ferrite in Sample A closely matched the experimental results with a permeability of 1.1, a saturation magnetization of 1600 Gauss, and an applied magnetization of 650 Gauss. On the other hand, Sample B showed general agreement with the

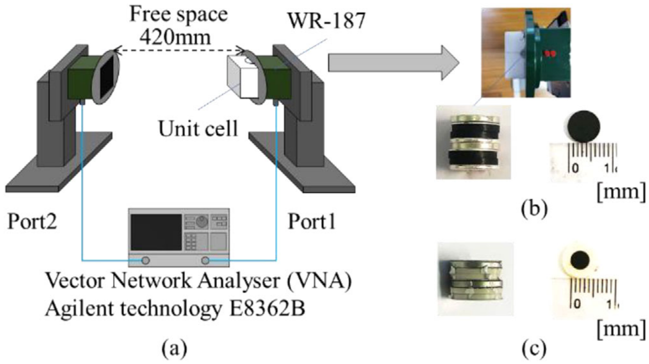

FIGURE 4 Experimental set-up (a), ferrite sample A configuration (b), and ferrite sample B configuration (c).

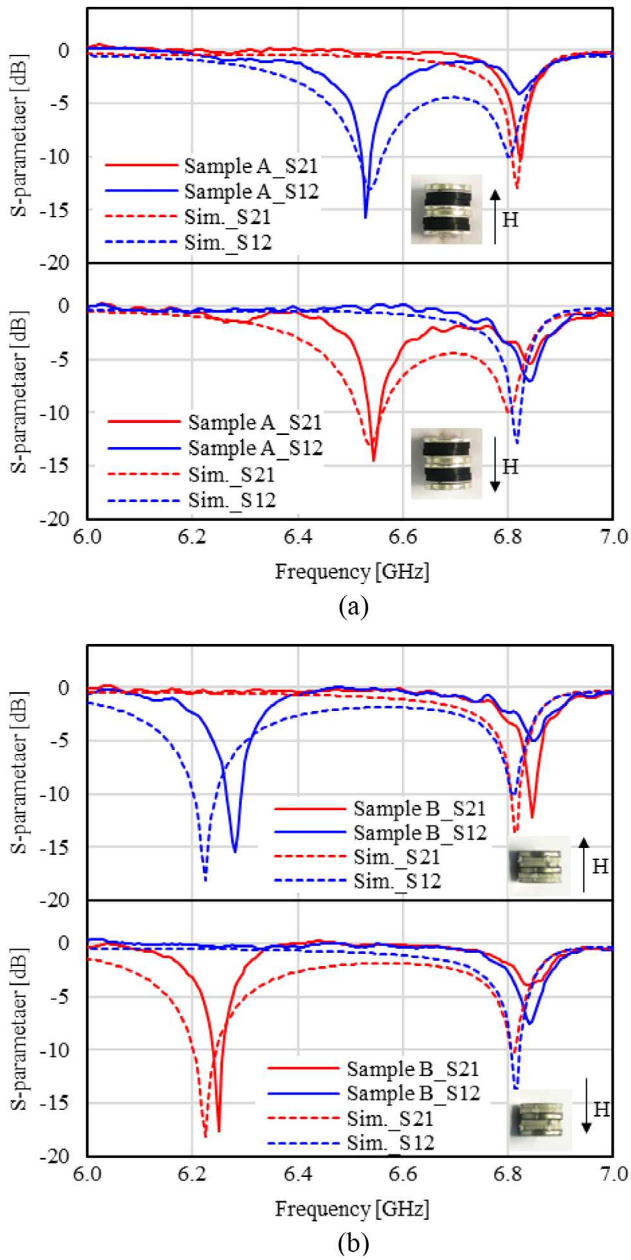

FIGURE 5 Experimental results for upward and downward magnetic fields for Sample A (a) and for Sample B (b).

experimental results with a permeability of 1.3, a saturation magnetization of 1600 Gauss, and an applied magnetization of 650 Gauss. Therefore, it is inferred that these ferrites are equivalent to G-1600 ferrite [11]. The differences between Samples A and B demonstrate that the frequency characteristics of nonreciprocity can be adjusted by altering the material properties (Figure 5).

The limited bandwidth can be attributed to the height of the ferrite, as discussed earlier. Ideally, to achieve a broader bandwidth, a magnetic field parallel to the height of ferrite is necessary. However, as the magnets are placed farther apart, parallelism deteriorates. To address this, we conducted experiments by stacking thin ferrite layers with magnets. This effect led to a reduction in isolation levels and a narrowing of the bandwidth.

A propagation null is observed at around 6.8 GHz in all results and is due to the geometry and location of the metal foil. This effect has been modeled and can be predicted; however, a detailed discussion is beyond the scope of this Letter and will be reported elsewhere. Consequently, both S_{21} and S_{12} are blocked.

4 | CONCLUSION

In this article, we introduced an innovative non-reciprocal metasurface characterized by its simple yet effective design. Through the utilization of a unit cell, we demonstrated its potential. Analytical results using an infinite plane model showcased the promise of achieving substantial isolation and broadband nonreciprocity. Additionally, experimental findings validated the non-reciprocal behavior of ferrite in two commercially available circulators, culminating in 15 dB isolation at 6.25 GHz and 6.5 GHz. In our future work, we plan to verify our findings through experimental testing using an array model, with the aim of expanding the operational bandwidth.

AUTHOR CONTRIBUTIONS

Kazuhiro Takahagi: Conceptualization; data curation; formal analysis; methodology; project administration; validation; visualization; writing—original draft. **Alan Tennant**: Funding acquisition; investigation; resources; software; supervision; 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 from the corresponding author upon reasonable request.

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