Proof-of-Concept Study on Two-bit Reconfigurable Reflectarray Using Magnetic Gear

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***Abstract*—In this letter, a reconfigurable reflectarray using a magnetic gear is proposed. A reflectarray element is composed of an array of four non-identical linear dipole elements arranged on a side surface of a cylindrical shell. As the reflectarray element rotates, phase of its scattering field is tunable. The reflectarray elements are mechanically rotatable using the magnetic gear in a contactless manner. A pair of cylindrical shell is fabricated by a 3D printing technology and array of small permanent magnets is loaded with the cylindrical shell. One magnetic gear is for the reflectarray element and four non-identical linear dipole elements are arranged on its side surface. Another magnetic gear is behind a reflecting plane and is driven by an actuator. The reflectarray element is designed by numerical simulation and its reflection coefficient is measured. A planar reflectarray working at 5.7 GHz band is fabricated and its beam scanning performance is demonstrated experimentally.**

***Index Terms*—Reflectarray, Magnetic gear, Reconfigurable**

I. Introduction

REFLECTARRAYS have been extensively studied for decades [1], [2]. Although the original reflectarrays were composed of array of waveguides [3], low-profile planar reflectarrays composed of microstrip elements have been popular and applied to wireless communications or satellite broadcasting [4]- [12]. On the other hand, reconfigurable reflectarrays, whose scattering patterns are tunable, have been studied so far. The reconfigurable reflectarrays are roughly categorized into electronically reconfigurable ones and mechanically reconfigurable ones.

Electronically reconfigurable reflectarrays are promising technologies because of high speed scanning and stable response [13]- [17]. Disadvantages of the electronically reconfigurable reflectarrays are nonlinearity, insertion loss of the diodes, and non-reciprocal performance.

Mechanically reconfigurable reflectarrays are possible counterparts to electronically reconfigurable ones [19]- [21]. The mechanically reconfigurable reflectarrays are free from nonlinearity and insertion loss of the diodes because their tunability stems from motors or actuators. As a result, scattering performance of the mechanically reconfigurable reflectarrays is reciprocal. Mechanically reconfigurable reflectarrays using rotational or height tunable elements have been proposed [22], [23]. Pattern reconfigurability of reflectarrays based on a mechanical displacement of a feed horn [24] or a reflecting plane [25]- [27] has been demonstrated. A 2-bit, 3D printed pattern reconfigurable reflectarray antenna has been developed and its beam scanning capability has been demonstrated [28].

In recent years, the mechanically reconfigurable reflectarrays using electromagnets have been developed [29]- [32]. Owing to the electromagnets, height of the reflectarray elements is tunable in a contactless manner. Therefore, a mechanical connection between reflectarray elements and actuators is unnecessary. A reflecting plane is kept without perforation, and perfect decoupling between reflectarray elements and actuators is achievable in operating frequency band. Although the mechanically reconfigurable reflectarrays using the electromagnets have advantages over conventional ones, their tunability is limited to single bit. Multi-bit or continuous tunability is not easily available using the electromagnets because of nonlinearity of magnetostatic force.

In this letter, a novel reconfigurable reflectarray using a magnetic gear is proposed. The magnetic gear is well-known as a counterpart of a mechanical one [33]- [36] and recently introduced to reconfigurable antennas by our group [37]. Although single bit tunability by on/off switching is only achievable by the electromagnets, multi-bit tunability by continuous rotation is achievable by the magnetic gear. A reflectarray element composed of multiple dipole elements arranged on a cylindrical surface is proposed and designed numerically. The reflectarray element is fabricated as dipole elements supported by a cylindrical shell made of PLA (Polylactic Acid). The cylindrical shell works as one part of the magnetic gear once array of small permanent magnets and ceramic bearing are loaded with it. Another part of the magnetic gear is made in the same manner and is arranged behind a reflecting plane. Reflection coefficient of the reflectarray element is measured and effect of the array of small permanent magnet is mainly discussed. Finally, planar reconfigurable reflectarray is fabricated and its beam scanning performance is measured.

This letter is organized as follows. Geometry and scattering performance of the proposed reflectarray element are shown in section II. After that, fabrication and measurement of the proposed reflectarray element are also demonstrated in section II. Pattern reconfigurability of the proposed reflectarray is demonstrated experimentally in section III. Finally, this paper is concluded in section IV.

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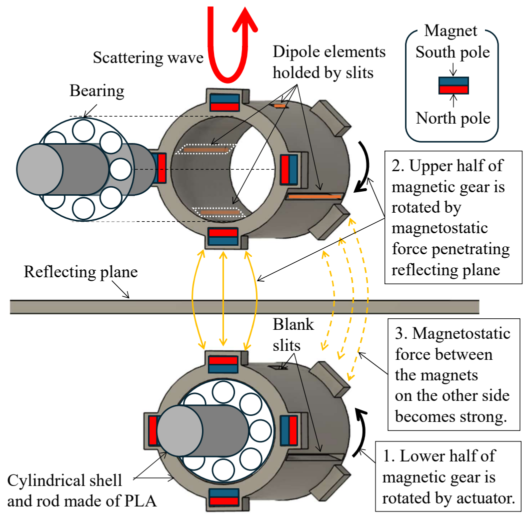

Fig. 1. Mechanism of rotatable reflectarray elements using magnetic gear.

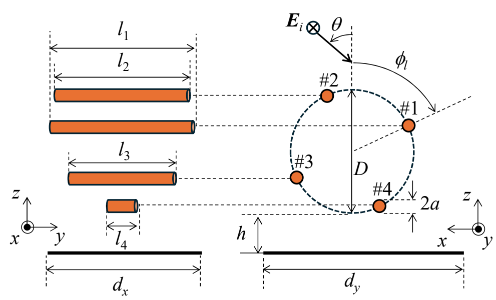

Fig. 2. Simulation model of rotatable reflectarray element using magnetic gear.

II. Rotatable Element Using Magnetic Gear

Fig. 1 illustrates mechanism of a proposed rotatable reflectarray element integrated with a magnetic gear. The proposed element is composed of four non-identical linear dipole elements, dielectric supporters such as a cylindrical shell/rod, eight permanent magnets, a bearing, and a reflecting plane. The dipole elements are holded by slits on the dielectric cylindrical shell. Eight small pockets for holding small permanent magnets are alternately arranged at the top/bottom parts of the dielectric cylindrical shell. A bearings is loaded with the top surface of the dielectric cylindrical shell. Dielectric rod penetrates center of the bearing and support the proposed element. Counterpart of the proposed element is behind the reflecting plane. According to the mechanism shown in Fig. 1, the proposed element rotates continuously once its counterpart behind the reflecting plane rotates mechanically in a contactless manner. Owing to the reflecting plane, the counterpart of the proposed element including an actuator, which is just for rotating the upper half of it, is isolated from incident wave. On the other hand, the counterpart of the proposed element is magnetostatically coupled with the upper half of it via magnetostatic force penetrating the reflecting plane. As a result, contactless tunability is achievable using the proposed element, and effect of the mechanical actuation system behind the reflecting plane on high frequency scattering performance

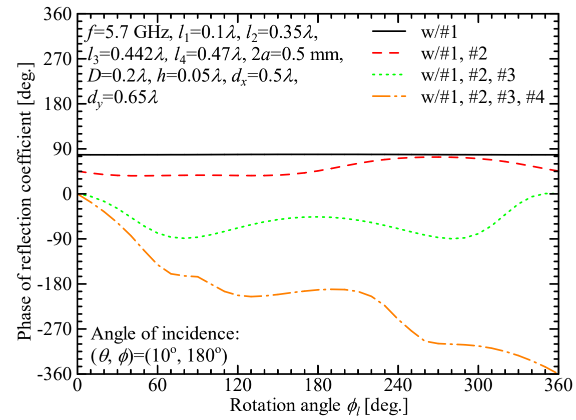

Fig. 3. Reflection coefficient of the proposed element. Magnitude of reflection coefficient is unity and omitted here.

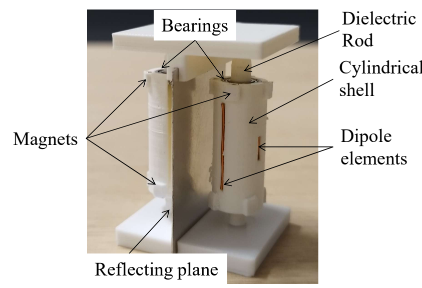

Fig. 4. Fabricated reflectarray element. As for implementation, single actuator controls single element.

of the proposed element is expected to be negligible.

Here, scattering performance of the proposed element is clarified by numerical simulation. Fig. 2 is a simplified model of the proposed rotatable reflectarray element. As illustrated in Fig. 2, dielectric supporters, permanent magnets and bearing are omitted here, and their effects on scattering performance of the proposed element is clarified experimentally, later. Therefore, the rotatable reflectarray element, i.e. four non-identical linear dipole elements backed by the reflecting plane, is modeled during numerical simulation. Fig. 3 is a simulated reflection coefficient under periodic boundary conditions (PBC). Numerical simulation was performed by method of moments (MoM) using commercial simulator software FEKO. The linear dipole elements and the reflecting plane are modeled as perfect electric conductor (PEC). According to Fig. 3, it is found that phase shift gradually increases as the number of dipole elements increases from one (w/#1) to four (w/#1, #2, #3, #4). It should be complemented that constant phase corresponding to w/#1 stems from short length ($= 0.1\lambda$) of the dipole element. Finally, it is demonstrated that the proposed elements composed of four non-identical linear dipole elements achieve phase shift over 360 deg.

Fig. 4 is a fabricated reflectarray element integrated with the magnetic gear and its operating frequency band is 5.7 GHz. The dielectric supporters including a cylindrical shell and rod were made of PLA and fabricated by a 3D printer Ultimaker S5. As mentioned earliear, infill rate of the PLA was 15 % and effective permittivity of the dielectric supporters

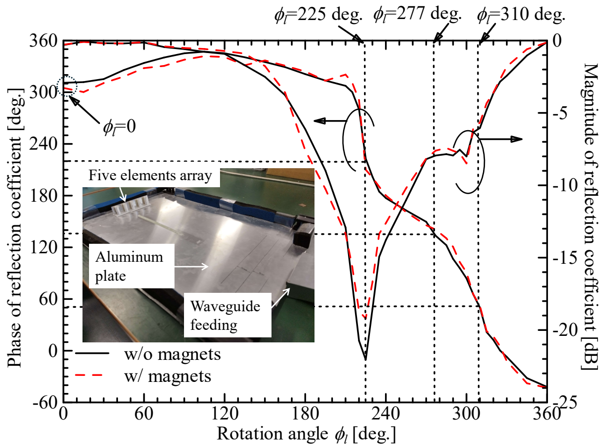

Fig. 5. Measured reflection coefficient (Picture shows inside of the PPW waveguide.). Phases corresponding to ϕ_l=0, 225, 277, 310 deg. are: 310, 222, 133, 50 deg., respectively.

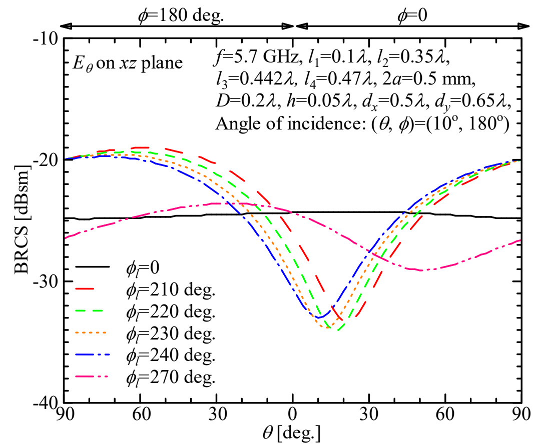

Fig. 6. BRCS patterns of single proposed element under PBC.

is 1.26 during fabrication. Small neodymium magnets whose diameter and thickness are 2 mm and 1 mm, respectively, are loaded with the pockets on the dielectric cylindrical shell. Magnets are much smaller than wavelength @ 5.7 GHz ($\approx$ 53 mm) and their effect on scattering performance is expected to be negligible. The dielectric cylindrical shell, bearing, and magnets are fabricated with dimensional errors at most 0.15 mm. The counterpart of the magnetic gear is behind the reflecting plane and it has been confirmed that the reflectarray element rotates as the counterpart rotates.

It should be noteworthy that implementation of the mechanical control system of the magnetic gear using an actuator is beyond the scope of this letter and all of the reflectarray elements were rotated directly by hand. On an implementation of the mechanical control system, following points should be in mind. From a viewpoint of multi-bit tunability, a miniaturized motor whose step angle is smaller than the minimum angle resolution corresponding to the tunability should be used. For example, step angle less than 90 deg. is required for two bit tunability. From a viewpoint of power consumption and low torque actuation, magnetic gear system should be lightweight as much as possible. Therefore, low infill rate of the magnetic gear frame and small permanent magnets are preferable. Response speed in msec order is achievable for specific application such as wireless communication once high performance stepping motor is used [38]. Low profileness can be achievable once the magnetic gear system with high gear ratio is used and size of the magnetic gear under the reflecting plane is reduced. Complex assembly is expected to be simplified by print-in-place approach during 3D printing.

Fig. 5 shows the measured reflection coefficient of the proposed element. During the measurement, a linear array composed of the five proposed elements was inside the parallel plate waveguide (PPW). The linear array was illuminated by a horn antenna connected to the edge of the PPW and S_{11} of the horn antenna was measured by a vector network analyzer in the same manner as previous works [28], [39]–[41]. Fig. 5, demonstrates:

1) Phase shift over 360 deg. as it rotates.
2) Small and limited effect of permanent magnets on the reflection coefficient.
3) Steep drop of the magnitude of the reflection coefficient around a specific rotation angle ϕ_l.

BRCS (bistatic radar cross section) patterns of single proposed element under PBC are simulated and demonstrated in Fig. 6 to find why the magnitude of the measured reflection coefficient drops at specific rotation angle. Fig. 6 demonstrates that null appears at broadside direction when the rotation angle is around 210$\sim$270 deg. Therefore, steep drop of the magnitude of the measured reflection coefficient stems from null of the scattering pattern of the proposed element. As mentioned later, rotation angle of the proposed element is chosen in a two-bit manner and its rotation angle in a reflectarray is individually different. Scattering pattern of a reflectarray is given by superposition of the scattering patterns of all elements and it is expected that the negative impact of a null in the scattering pattern of an individual reflectarray element on the overall scattering pattern of the reflectarray is mitigated.

Loss of the proposed element can be estimated from the measured magnitude of reflection coefficient shown in Fig. 5. As described in [28], the measured magnitude of reflection coefficient corresponding to 0 dB is equivalent to that of a metallic plate with the same size. Therefore, drop from 0 dB is loss of the proposed element except for impact of null of the scattering pattern of the proposed element on it. From the magnitude of the reflection coefficient at $\phi_l = 0$, which is unaffected by the null in the scattering pattern of the proposed element as shown in Fig. 6, the loss is estimated to be approximately $\sim$0.3 dB.

III. Reconfigurable Reflectarrays Using Magnetic Gear

The fabricated prototype is a planar reflectarray composed of 8×6 elements backed by a reflecting plane. Rotation angles of the reflectarray elements are chosen from $\phi_l = 0, 225, 277, 310$ deg. in a two-bit manner. Fig. 7 includes a picture of the fabricated prototype and measured BRCS patterns in H-plane. It is found that main beam of the fabricated prototype is steerable to specific angle and measured BRCS

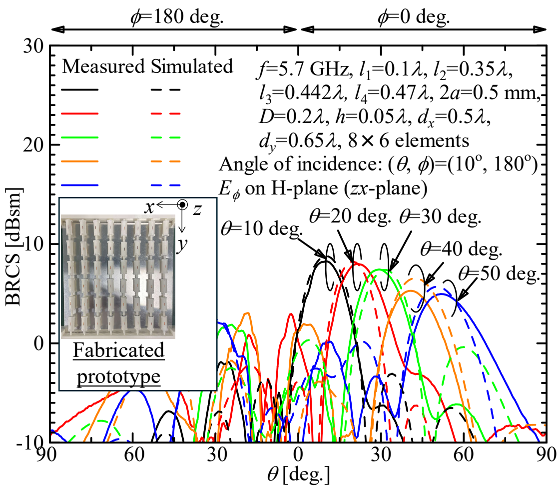

Fig. 7. Measured and simulated BRCS patterns in H-plane.

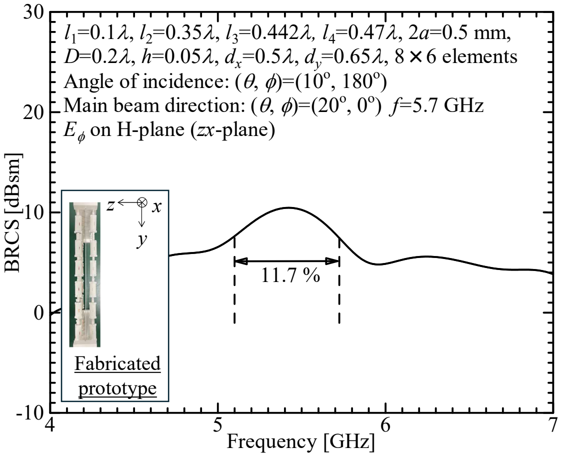

Fig. 8. Measured bandwidth.

levels agree well with those of simulated ones except for small difference. Small difference between simulated and measured BRCS levels comes from: misalignment of the rotation angle, fabrication error, and loss. Except for small difference between simulated and measured BRCS levels, pattern reconfigurablility of the fabricated reflectarray using the proposed elements has been demonstrated well. Measured cross-polarization level was below -3 dBsm for all measurement results. Fig. 8 is measured 3 dB bandwidth of the fabricated prototype and measured 3 dB bandwidth is 11.7 %.

Finally, scattering performance of the proposed reflectarray is compared with that of previous works in TABLE I. It is found that multi-bit tunability of the proposed element outperforms previous ones. Also, scattering performances of the reconfigurable reflectarray using the proposed elements such as scanning angle, scanning loss, and fractional bandwidth are comparable to those of previous ones. Fig. 9 shows rotation angles of reflectarray elements corresponding to beam scanning angles. As discussed earliear, the proposed element has null around $\theta = 10 \sim 20$ deg. at specific rotation angle, i.e. $\phi_l = 225$ deg. and it can negatively impacts on the scattering patterns of the proposed reflectarray. However, according to

TABLE I
PERFORMANCE COMPARISON OF RECONFIGURABLE REFLECTARRAYS.

Mechanism	Freq. [GHz]	Phase shift [deg.] (Tunability)	Scanning angle (Scanning loss)	Fractional BW [%]
Actuator [26]	5	360 (Continuous)	< 60 deg. (4.5 dB)	N/A
Actuator [28]	4.3	270 (2-bit)	< 50 deg. (4.8 dB)	9.2 (1 dB drop)
Electromagnet [29]	4.4	180 (1-bit)	< 45 deg. (3.2 dB)	9.2 (1 dB drop)
Electromagnet [32]	5.8	267 (1-bit)	< 50 deg. (3.9 dB)	17 (3 dB drop)
Magnetic gear (This work)	5.7	385 (2-bit)	< 50 deg. (3.1 dB)	11.7 (3 dB drop)

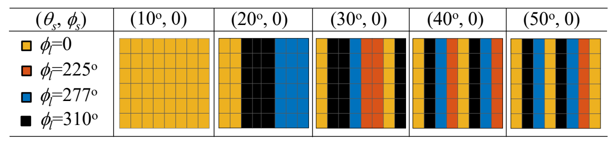

Fig. 9. Colormaps of rotation angles of reflectarray elements corresponding to beam scanning angles.

Fig. 9 and TABLE I, no reflectarray elements corresponding to $\phi_l = 225$ deg. are found at colormaps of $\theta_s = 10$ and 20 deg. and resultant scanning loss is small. Therefore, it can be concluded that a contactless actuation system using the magnetic gear achieves multi-bit phase tunability, without negative impacts on scattering performances.

IV. CONCLUSION

In this letter, a novel reconfigurable reflectarray using a magnetic gear has been proposed. The magnetic gear can transfer torque by magnetostatic force penetrating a reflecting plane. As a result, the reflectarray element is rotatable in a contactless manner once the magnetic gear is integrated with it. A rotatable reflectarray element composed of four non-identical dipole elements is designed and its scattering performance was demonstrated. Two-bit reconfigurable reflectarray was fabricated and its beam scanning performance was demonstrated experimentally.

As shown in this letter, contactless actuation system using the magnetic gear has a couple of advantages over conventional ones. The first one is perforation free reflecting plane that contributes to eliminate leakage from holes and keep perfect decoupling between reflectarray elements and actuators. The second one is frictionless tunability that contributes to maintenance free nature [42]–[44]. For example, the contactless actuation system using the magnetic gear outperforms [22] and [23] from the viewpoint of the first one, and outperforms [26] and [28] from the viewpoint of the second one. This letter has demonstrated that these advantages are compatible with multi-bit tunability, which is not achievable for electromagnets counterparts. Therefore, the contactless actuation system using the magnetic gear has a potential to outperform the conventional mechanical actuation systems. Full implementation of the contactless actuation system is a future work.

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