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LETTER

A novel electromagnet-controlled reflectarray element employing 1-bit height locking system with low power consumption

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Abstract A novel 1-bit mechanically controlled reflectarray element features in high efficiency is proposed. The element is actuated by an electromagnet under ground plane thus opening via hole or slot is unnecessary. A locking system is designed to lock the steel patch in two different height, which can avoid high power consumption of electromagnet in either of the states. The mechanical performance is discussed in detail and the scattering characteristics of the element are experimentally and numerically validated. A 10×10 reflectarray antenna is modeled and its beam scanning ability is demonstrated through a MoM fullwave simulation.

Keywords: reflectarray, antennas, periodic structure, electromagnets, on-off control

Classification: Antennas and propagation

1. Introduction

Mechanically controlled reflectarray is a kind of reflectarray that uses array element with mechanical actuator which can tune the reflection phase [1, 2]. Avoid using non-linear devices such as diodes and varactors, mechanically controlled reflectarray has advantages such as high aperture efficiency and low quantization loss. However, due to slow speed and large size of the mechanical actuator, its disadvantage lies in slow beam scanning speed and lower operating frequency band [3].

Numerous methods have been performed on realizing mechanically controlled reflectarray. Mechanically controlled reflectarray that can tune the reflection phase by tuning the height of the metal part was proposed [4]. One of the works propose mechanically rotating the element to realize phase tunability [5]. Methods such as rotating the primary source of the reflectarray antenna [6], or deforming the ground plane were also proposed [7]. Recently, techniques based on tuning the transmission length of Non-Radiative Dielectric (NRD) waveguide by inserting a blade was proposed [8]. This quasi-TEM wave transmission line method enable wide band possibility in mechanically controlled reflectarray.

To change the phase of each mechanically controlled element independently, traditional reflectarray cannot avoid open via hole or slot on the ground plane to mechanically connect the element and motor. The opened via hole or slot can cause insertion loss since partial power will be transmitted to the backside of the reflectarray [4]. To solve this problem, an electromagnet-controlled reflectarray antenna was proposed [9]. A dipole strip element with a steel patch below its geometry center was taped on a polystyrene film. The electromagnet underneath the ground plane provide magneto-static force that can attract the steel patch. The deformation of dipole strip results in the 180° phase change. The magnetic field can penetrate the ground plane, thus opening holes on the ground is unnecessary. Though high aperture efficiency feature was found in this work, on-state power consumption (around 0.5 W for single element) was mentioned as a main challenge in this work. A method to save the power in electromagnet is yet to be found.

In this letter, a design of electromagnets-controlled reflectarray element employing 1-bit position locking system is proposed. The proposed element is actuated by an electromagnet under the ground plane. A position locking system is applied to help the steel patch element to lock its position in 2 different heights, thus power consumption in either of states is unnecessary. Different height of the patch results phase shift of reflection wave, and 1-bit phase shift is achieved. The proposed element feasibility is analyzed in its mechanical and scattering characteristics, and a fullwave simulation is performed to demonstrate its beam scanning ability.

2. Element design and working principle

The model of the proposed electromagnet-controlled element is demonstrated in Fig. 1. The proposed element can be divided into 2 parts, an extensible part and a fixed part. The extensible part, having a thickness in t_e, is connected to the fixed part by a 2-cantilever system. The cantilevers are designed in S-turn, where the length and width of each turn on the arm is expressed in l_c and w_c, respectively. At the center of the extensible part is a rectangular platform with dimension in length l_p and width w_p. At the 2 ends of the rectangular platform, there are 2 rods stick out with length l_r and width w_r. A steel patch is taped onto the rectangular platform and their sizes are exactly the same. The fixed part, having a height in H, is beneath the extensible part. Under each rod of the rectangular platform, there are 2 triangular stoppers stick out from the inner side of the fixed part wall. A zoom-in look of the stoppers can be found in Fig. 2(a), where the 2 triangles are right-angle ones with height of h_t

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and width of w_t. The distance from the bottom of the upper triangle to the ground plane is h. An aluminum ground plane is placed at the bottom of the proposed element. The element periodicy in x-axis and y-axis is L_x and L_y, respectively.

The phase tunning mechanism of the proposed electromagnet-controlled element is a resonant approach. It is well-known that the phase of the reflection coefficient can be tunned by changing the height of the metal part (e.g. steel patch) on the element. Actuation of the height can be realized by the locking system and the electromagnet. The locking system is composed of the rods on the extensible part and the stoppers on the fixed part. The S-turns on the cantilevers let the extensible part become a spring system that can move both along z-axis and x-axis. As shown in Fig. 2(b), in the beginning, the rods are at the state 1 position and the steel patch is in height $H + t_e$. When turn on the electromagnet, due to the presence of the static magnetic field, the steel patch will be pulled down to the ground plane, whereas the rods will follow the red curve that move over the upper triangular stopper. When the electromagnet is turned off, the magneto-static force disappear, and the steel patch will restore to the original position. Due to the existence of the upper stopper, the rods will be stuck to state 2 position, thus the steel patch will be locked in height h. By turning on the electromagnet again and release it, the rods will move

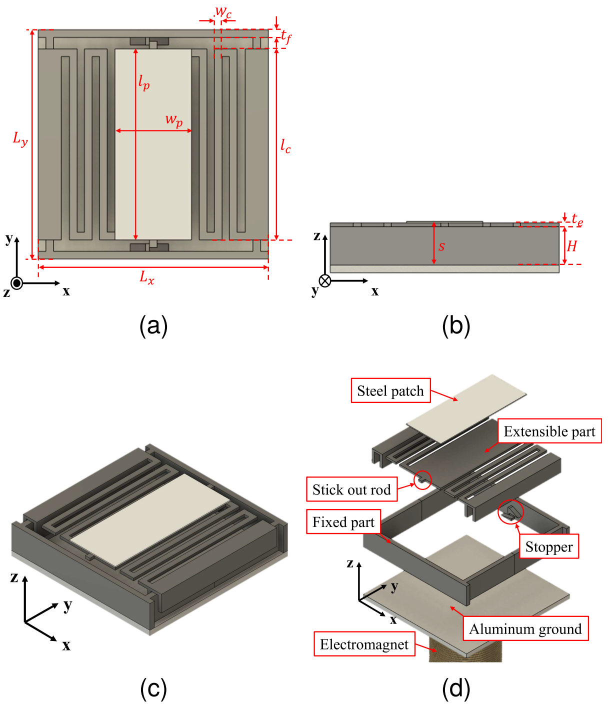


Fig. 1 Demonstration of the proposed electromagnet-controlled element with locking system.

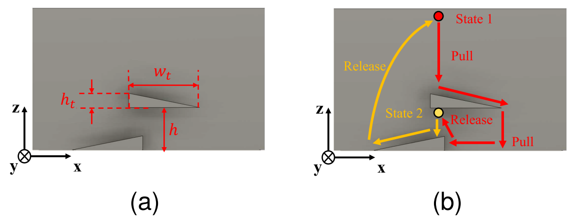


Fig. 2 Zoom-in of the locking system on the fixied part of the proposed element.

along yellow lines and the patch will be restored to the state 1 position. In this design methodology, the proposed element can be actuated in 2 different height by simply turning on the electromagnet from time to time.

3. Element mechanical and scattering characteristics

The mechanical system of the extensible part can be seen as two cantilevers in parallel that their one end is clamped to the fixed part. According to the previous study [9], the displacement $\delta = H - s$ brought by a static force applying to the center of the rectangular platform will be:

$$\delta = H - s = \frac{|\boldsymbol{F}|L^3}{8Ew_c t_e^3}, \tag{1}$$

where L is the length of a single cantilever. In this case, total summation of length of S-turn cantilever $l_c = 25$ mm is taken (e.g. $L = 3\times l_c = 75$ mm). Due to the fabrication limitation of the 3D printer, the width of cantilever w_c and the thickness of the extensible part t_e is designed to be as small as possible. As a results $w_c = 1$ mm and $t_e = 1$ mm. $E = 3.0$ GPa is the Young's modulus of the PLA material. Here, since two cantilevers in parallel will result in a double of Hook's coefficient, the denominator in the fraction is taken as 8 rather than 4 in previous work [9]. Substitute all the parameters, one can find that to actuate such mechanical system to make a 5 mm displacement in z-axis would require 0.28 N static force.

To realize such static force, the static magnetic field $\boldsymbol{B}$ can be derived using the following equation:

$$\boldsymbol{F} = -\frac{|\boldsymbol{B}|^2 l_p w_p}{2\mu_0}\hat{z}, \tag{2}$$

where l_p and w_p taken as 25 mm and 10 mm, respectively. μ_0 is the free space permeability. Substitute all the parameters, it is found that 37.4 mT static magnetic field is needed to generate force $\boldsymbol{F}$. An electromagnet that can generate static magnetic field higher than 37.4 mT such as TMB-1330-50LT (maximum 90 mT at 5 mm [10]) and TMB-1370 (maximum 120 mT at 5 mm [11]) can be a good candidates. Due to the size limitation, TMB-1330-50LT would be a feasible one for the proposed element. In this work, all of the element is tuned manually between state 1 and state 2. The experimental validation of the mechanical characteristics of the proposed element controlled by an electromagnet will be remained as a future work.

A 1-dimensional 5 elements reflectarray is fabricated and measured, whereas the extensible parts and the fixed parts of the proposed element is fabricated using commercial 3D-printer Guiders IIs. The fabricated prototype is shown in Fig. 3. The 3D-printing material is Poly-Lactic Acid (PLA) with complex relative permittivity $\epsilon_r^e \approx 1.25 + j0.01$

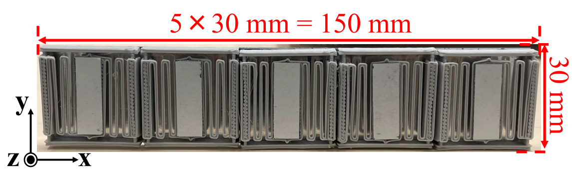


Fig. 3 Fabricated 1-dimensional 5 elements reflectarray for scattering performance characterization in the PPW

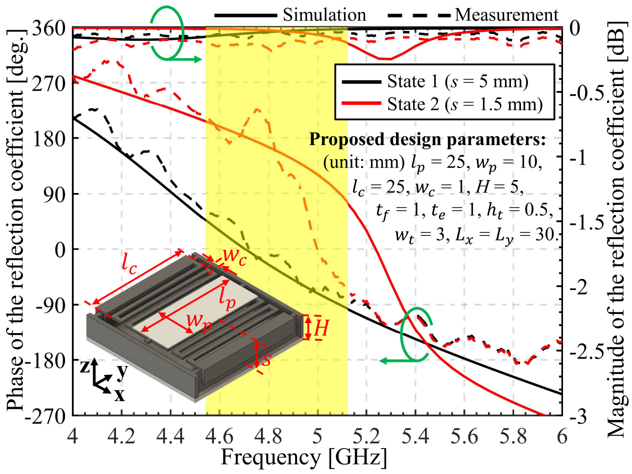


Fig. 4 The scattering characteristics of the proposed electromagnet-controlled element.

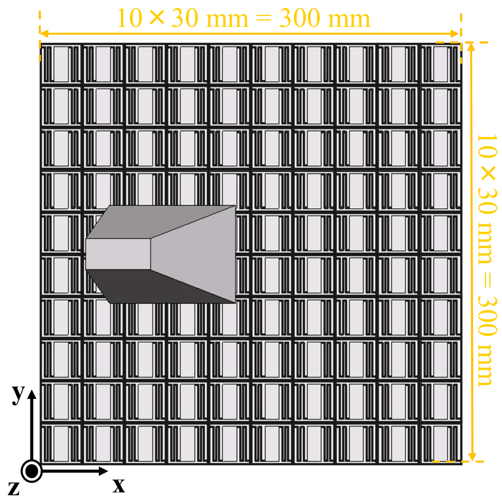
(f = 4.7 GHz). The measurement system is a parallel plate waveguide (PPW), and the 1-dimensional array is placed at the end of the PPW and TEM-mode guided wave is excited. The scattering characteristics is measured by the reflection coefficient when turning all 5 elements together to state 1 or state 2. The reflection coefficient is measured at the port of VNA and the value is normalized by an aluminum plate of same size with the 1-dimensional array (e.g. $5L_x \times L_y$ = 150 mm × 30 mm).

The measured results are shown in Fig. 4, whereas the simulation results comes from a Method of Moment (MoM) full-wave simulation using the commercial software FEKO. As shown in the results, the measured reflection coefficients agree well with the simulated ones. The proposed electromagnet-controlled element can realize 180° phase difference around 4.7 GHz with maximum magnitude drop around 0.25 dB. The fractional bandwidth that element can maintain phase difference in 160° ~ 200° is around 12.8%. The results shows that the proposed element clarified 1-bit phase shift with a low magnitude loss around 0.25 dB.

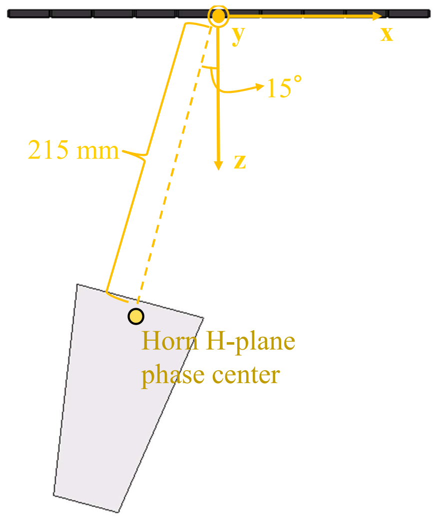
4. Reflectarray antenna performance validation

The proposed element is formed into a 10×10 reflectarray and its radiation performance is validated through MoM simulation. The simulation model is shown in Fig. 5. A C-band standard gain horn antenna is chosen to be the primary source of the total reflectarray antenna system. The H-plane phase center of the horn is placed at (215 mm, θ_f, ϕ_f), where the coordinates are relative to the geometry center of the 10×10 reflectarray surface. In this work, (θ_f, ϕ_f) is taken as (10°, 180°) to avoid feed blockage in the broadside direction. The distance from reflectarray to horn phase center r_f is optimized so that the maximum aperture efficiency can be obtained. The detailed optimization method can be found in our previous work [9], thus the derivation is omitted here. According to the optimization, the spill over loss is around −0.66 dB and the illumination loss is around −0.74 dB.

The phase assignment strategy is based on compensating the point source incident wave so that the scattering can be a plane wave. Firstly, the ideal compensation phase of i^{th} element Ψ_i is calculated as follows:



(a)



(b)

Fig. 5 The reflectarray antenna model

$$\Psi_i = k\,(R_i - \boldsymbol{r}_i \cdot \hat{\boldsymbol{r}}_s) + \Psi_0, \tag{3}$$

where k is the free space wave number, R_i is the i^{th} element's distance to origin, $\boldsymbol{r}_i$ is the position vector of i^{th} element and $\hat{\boldsymbol{r}}_s = (1, \theta_s, \phi_s)$ is the unit vector toward main beam direction. Ψ_0, which is taken as 0 for all scenarios in this work, is the bias phase that provide an additional freedom to optimize the phase distribution over the reflectarray aperture. After deriving all the Ψ_i for each element, the quantize states of each element is assigned as follows:

$$\Psi_i^{1\text{bit}} = \begin{cases} \Psi_{\text{state1}} & , \Psi_i \in [0°, 90°] \cup [270°, 360°] \\ \Psi_{\text{state2}} & , \Psi_i \in [90°, 270°] \end{cases}. \tag{4}$$

The phase assignment of all element for beam scanning in xoz-plane is shown in Fig. 6.

The gain patterns of the proposed reflectarray antenna is shown in Fig. 7. It is shown that the maximum simulated gain of the proposed reflectarray antenna is around 19.5 dBi. The maximum gain can be obtained at (θ_s, ϕ_s) = (15°, 0), which is the specular direction of the scattering from the source. The aperture efficiency can be calculated by the

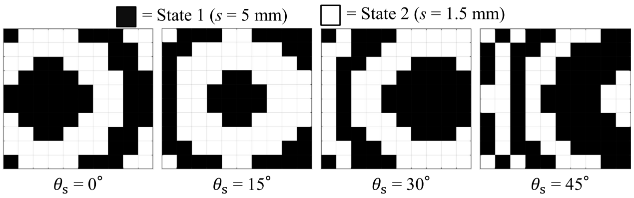


Fig. 6 The assigned steel patch height s to each element of the proposed RA antenna system for main beam steering to xoz-plane ($\varphi_s = 0$).

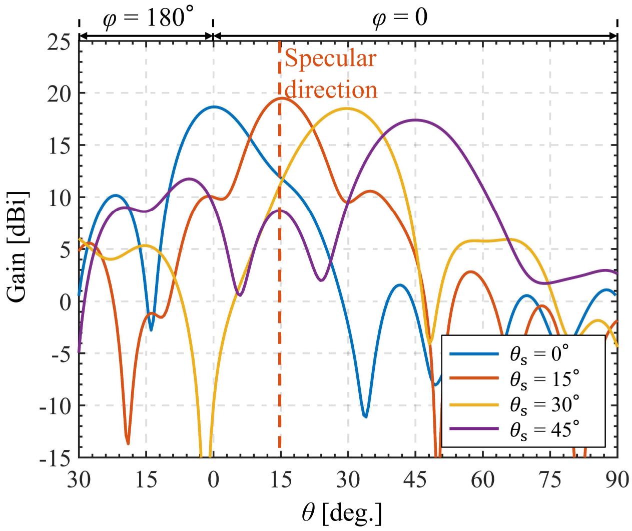


Fig. 7 The simulated radiation performance of the reflectarray antenna using proposed elements with beam scanning in xoz-plane ($\varphi_s = 0$).

ratio of the gain to the maximum possible directivity D of the same physical aperture size A as following:

$$D = \frac{4\pi A}{\lambda^2}, \tag{5}$$

where λ is the wavelength at 4.7 GHz. The maximum aperture efficiency accordingly is thus 32%, which is comparable to the previous work [9] around 34%. As the main beam scan to large angle, the gain gradually decrease and the pattern starts to distort due to the reduction of physical aperture size and imperfect phase compensation. Overall to say, the reflectarray using the proposed element demonstrated beam scanning ability with acceptable aperture efficiency, while the either of the two states of all elements consume power.

5. Conclusion

In this letter, an novel 1-bit mechanically controlled reflectarray element features in high efficiency was proposed. The element was actuated by an electromagnet under ground plane thus opening via hole or slot was unnecessary. A locking system was designed to lock the steel patch in 2 different height, which can avoid high power consumption of electromagnet in either of the two states. The mechanical performance was discussed in detail and the scattering characteristics of the element were experimentally and numerically validated. A 10×10 reflectarray antenna was modeled and its beam scanning ability was demonstrated through a MoM fullwave simulation.

Though the fabrication of the reflectarray antenna and experiment validation on beam scanning was not performed, several solution is provided as follows: Firstly, the prototype of the reflectarray antenna system can be fabricated by 3D printer Flash Forge Guiders IIs. The average fabrication time for a single element is around 30 minutes, whereas a 10×10 array would cost 50 hours. The experiment can be carried out in an EM anechoic room using a VNA and a turn table. These approaches are remained as future work and the performance will be further validated.

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