A New Class of Method With TE/TM Wave Decomposition and Superposition Enabling High-Efficiency Transmitarray Antenna

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***Abstract*—The first-of-its-kind TE/TM wave decomposition and superposition methods for a rotational arrangement to the polarization of the unit cell are proposed and demonstrated computationally and experimentally, which can significantly enhance the aperture efficiency of the low-profile transmitarray (TA) antenna. Phase variation on the TA aperture stemming from the unit cell arrangement method was calculated by extracting the coupling coefficient between unit cells through the reflection coefficient Floquet response using TE/TM wave decomposition and superposition methods to validate the utility of the proposed unit cell arrangement. The proposed TA antenna exhibits a low focal length to diameter (F/D) ratio of 0.33 and an aperture efficiency of 40.5% at a center frequency of 3.5 GHz with an aperture size of $5.1\lambda_o \times 5.1\lambda_o$.**

***Index Terms*—Transmitarray (TA), TE/TM wave, unit cell, frequency selective surface (FSS), low profile, focal length to diameter ratio (F/D).**

I. Introduction

Transmitarrays (TA) have recently been in the limelight due to their various advantages in many fields. Multibeam operation for spatial beamforming reported in [1] can be supported as well as increasing the gain of a feeding antenna by utilizing a thin FSS structure or combining an FSS and a patch structure [2], [3]. However, in most cases, a single antenna such as a horn, patch and dipole is used as the feed antenna [1], [2], [3]. In the case of a single antenna, not only the phase distribution but also the power density incident on the TA aperture is relatively uniform. In the case of a sub-array antenna, the phase distribution and power density are irregular due to the difference in radiation phase between radiators constituting the sub-array. Besides, a different approach to the arrangement of unit cells constituting the TA is required when the array direction and the polarization direction are different. In this paper, high aperture efficiency was achieved through the arrangement of unit cells rotated based on the polarization of the aforementioned feed antenna with the decomposition and superposition methods of TE/TM wave. The reason for the higher gain compared to the unrotated ones was analyzed by calculating the phase variation based on the coupling coefficient and this was verified through measurement.

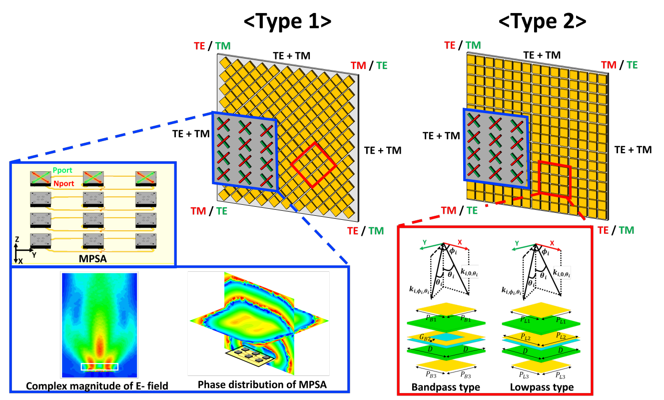


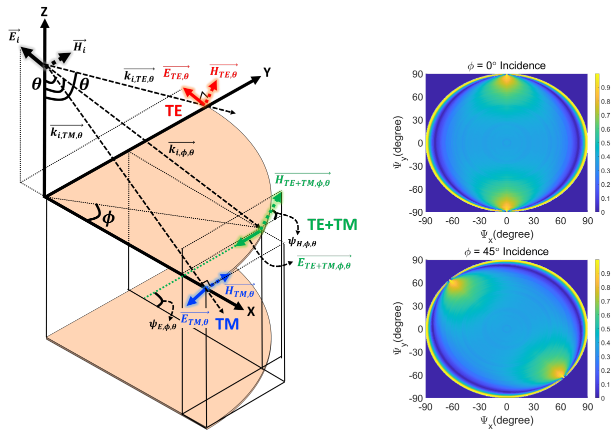
Fig. 1. Exploded view of the unit cells and different types of TA depending on the unit cell rotation deployment using the multi-port sub-array antenna as feeding the antenna.

II. Design of the Transmitarray Antenna with Rotated Unit Cell Arrangement

A. Configuration of Different Types TA and Feeding Antenna

In Fig. 1, two types of TA can be identified, in the case of Type 1 TA, the direction of polarization and the arrangement direction of unit cells constituting the TA coincide. In Type 2 TA, the direction of polarization and the arrangement direction of unit cells form a specific angle (i.e., 45°), having an equal reference phase with the Type 1 TA. For the antenna feeding the TA, 3 patches supporting $\pm 45^\circ$ slant dual polarization constitute one sub-array, and 4 sub-arrays constitute one antenna structure. As shown in Fig. 1, this multi-port sub-array (MPSA) antenna has a different phase distribution and power distribution than a typical feeding antenna such as a horn antenna.

The TA used in Fig. 1 consists of two types of FSS unit cell structures: bandpass type and lowpass type [2]. If the unit cell satisfies the condition of rotation symmetry for an angle of 90 degrees, the response of the unit cell is the same even if the polarization of the electric field rotates by ϕ_i around the z-axis as shown in Fig. 1. In addition, even if it rotates by ϕ_i and forms an incident angle by θ_i at the same time, the response of the unit cell is the same as when ϕ_i = 0°.



(a) (b)

Fig. 2. (a) 3D configuration of the region where TE, TM, and TE+TM combined waves are synthesized on the TA aperture. (b) Reflection coefficient magnitude response of bandpass unit cell at 3.5 GHz by phase difference in x and y-axis direction occurring in the unit cell due to oblique incidence.

B. Response Analysis of Incident Waves with Mixed TE/TM Wave through Decomposition and Superposition Methods

Through Fig. 2, the Floquet unit cell response in the region where TE and TM waves are combined can be obtained. The $\overrightarrow{k_{i,\phi,\theta}}$ is a wave vector in the TE+TM region, and the E and H fields in the TE+TM region must be orthogonal to the wave vector. As a result, the response of a wave incident in a direction rotated by θ and ϕ can be expressed superimposed on the basis of a Floquet simulation of a unit cell of TM and TE waves incident at an angle of θ as shown in (1).

$$S_{\phi,\theta}=A\cdot S_{\theta,TM}+B\cdot S_{\theta,TE} \quad A=\frac{sin\psi_{E,\phi,\theta}}{sin\theta},\ B=\frac{sin(\theta-\psi_{E,\phi,\theta})}{sin\theta} \tag{1}$$

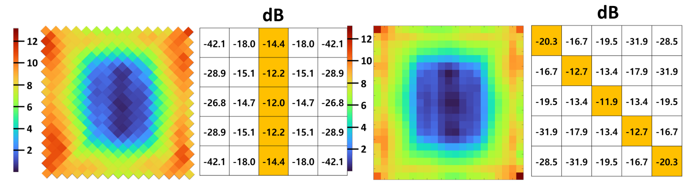
$$\psi_{E,\phi,\theta}=tan^{-1}(tan\theta cos\phi) \tag{2}$$

$$\Psi_x=kD\cdot sin\theta cos\phi,\ \Psi_y=kD\cdot sin\theta sin\phi \tag{3}$$

Ψ_x, Ψ_y represent the phase difference between unit cells in the x-axis and y-axis directions, respectively. Fig. 2.(b) shows the magnitude of the bandpass unit cell's reflection coefficient at 3.5 GHz in the 4th quadrant based on (1), and it can be seen that the position of the point with the largest reflection coefficient (i.e., TE wave region) changes as the unit cell rotates. Accordingly, the TA gain can be increased by rotating the unit cell to match an area with a low reflection coefficient with an area where large power is incident.

C. Calculation of Phase Variation in Accord with the Unit Cell Arrangement Method

Mutual coupling between adjacent unit cells can be calculated as (4). M and n mean the number of unit cells away from the reference unit cell toward the x-axis and y-axis directions, respectively, and S^{FL} represents the reflection coefficient of the array element under Floquet excitation conditions. Fig. 3 shows the mutual coupling coefficient of Type 1 and Type 2 TA using (4). The direction colored in yellow indicates the incident polarization direction. Considering the phase distribution formed in each TA aperture and regarding the coupling coefficient formed in the unit cell as a weight factor, examining the degree of the phase difference between the reference cell and the neighboring cells, Type 1 has a more severe phase variation than Type 2 on average, as shown in Fig. 3. Through this, it can be seen that the phase variation occurring at the aperture varies depending on the method of capturing the phase, that is, the method of disposing of the unit cells.

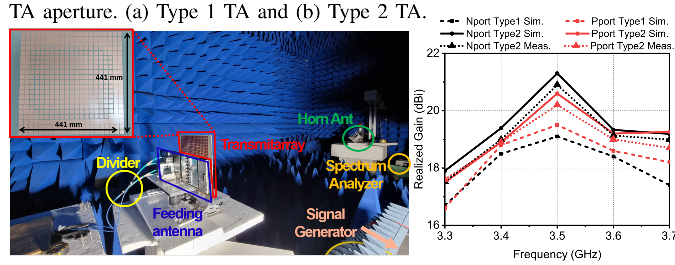


-42.1	-18.0	-14.4	-18.0	-42.1
-28.9	-15.1	-12.2	-15.1	-28.9
-26.8	-14.7	-12.0	-14.7	-26.8
-28.9	-15.1	-12.2	-15.1	-28.9
-42.1	-18.0	-14.4	-18.0	-42.1

-20.3	-16.7	-19.5	-31.9	-28.5
-16.7	-12.7	-13.4	-17.9	-31.9
-19.5	-13.4	-11.9	-13.4	-19.5
-31.9	-17.9	-13.4	-12.7	-16.7
-28.5	-31.9	-19.5	-16.7	-20.3

(a) (b)

Fig. 3. Phase variation considering the coupling coefficient formed on the TA aperture. (a) Type 1 TA and (b) Type 2 TA.



(a) (b)

Fig. 4. (a) Measurement setup and (b) Simulated and measured gain level of the proposed TA antenna.

$$S_{mn}=\frac{1}{4\pi^2}\int_{-\pi}^{\pi}\int_{-\pi}^{\pi}S^{FL}(\Psi_x,\Psi_y)exp[j(m\Psi_x+n\Psi_y)]d\Psi_x d\Psi_y \tag{4}$$

III. Measurement and Results

The measured and simulated gain of the proposed TA antenna with the measurement setup are shown in Fig. 4. Type 2 TA showed a gain of 21.3 dB and an aperture efficiency of 40.5% based on Nport at 3.5 GHz, which is 16.1% higher than Type 1 at 24.4%.

IV. Conclusion

In this paper, the rotational arrangement of the unit cell employing the first-of-its-kind TE/TM wave decomposition and superposition methods was applied to the low-profile TA antenna with high aperture efficiency. The proposed TA antenna was able to obtain about twice the increase in aperture efficiency compared to the TA antenna that applied the unit cell arrangement perpendicular to the polarization.

Acknowledgment

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