[若手招待講演]透過アレーアンテナの高性能化と多機能化に関する研究

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Research on Transmitarray Antennas with Enhanced Performance and Expanded Functionalities

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Abstract This paper presents the research conducted during the Ph.D. study in Tohoku University. Advanced analysis methods and novel designs of transmitarray antennas, which are one kind of hybrid high-gain antennas combining both the advantages of lens antennas and phased array antennas, are investigated. Specifically, three different aspects of transmitarray antennas, as beam-shaping operation, multifunctional operation, and wideband operation, are studied. Here, basic ideas, design principles, and research results are presented in detail for each aspect after briefly introducing the concept of transmitarray antennas.

Keywords Antenna synthesis, Beam-shaping, Bidirectional, Multifunctional, Periodic structure, Transmitarrays, Wideband

1. Introduction

For being one of the most prominent types of high gain antennas, transmitarray antennas have attract considerable attentions in recent years. As one kind of hybrid antennas, transmitarray antennas combine both the advantages of conventional lens antennas and phased array antennas. They are usually composed of a spatially-deployed source feed and a flat transmitarray aperture. The aperture is typically consisting of a large number of transmitarray elements, each of which can be individually controlled to provide desired transmission phase and amplitude. The working principle lies in compensating the spatial phase delay resulting from the source feed to each element on the aperture to add the transmitted fields either constructively or destructively for intended purposes. This work covers three different major topics required to be tackled and investigated on transmitarray antennas with enhanced performance and expanded functionalities.

Firstly, an amplitude-phase synthesis method that involves complete control of complex transmission coefficient is developed for designing transmitarray antennas with an expected shaped radiation beam. The amplitude-phase synthesis method is composed of two parts as transmitarray element design and transmitarray synthesis. Compared with conventional phase-only synthesis method, the developed amplitude-phase synthesis method offers feature of flexible beam-shaping capability.

Secondly, in order to enhance the efficiency of the transmit-reflect-combined-array antennas, a novel four-layer polarization-dependent multifunctional unit cell is proposed with the features of simultaneous and decoupled control of transmission phase and reflection phase [1]. Besides, the element demonstrates stable responses under oblique incidence, which is vital for the antenna efficiency. The resulting antenna provides better performance in terms of aperture efficiency than existing designs. Moreover, by simply slanting the source feed, simultaneously bidirectional capability of the antenna is achieved.

Thirdly, in order to realize wideband transmitarray antennas in a low-cost and reduced-complexity manner, an

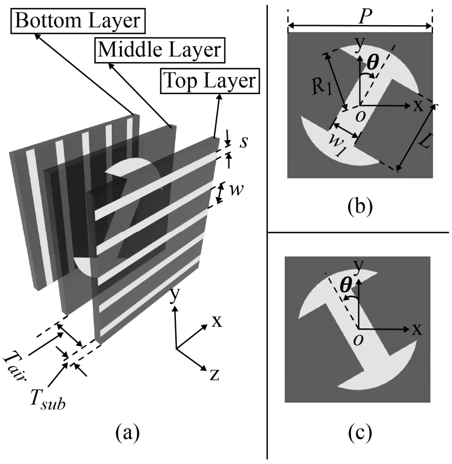

Fig. 1 Unit cell view (a) 3-D schematic; (b) Top view of the middle layer; (c) Mirrored structure of the middle layer. $s = 0.8$, $w = 2.2$, $T_{air} = 4$, $T_{sub} = 0.8$, $w_1 = 3$, $R_1 = 6.5, 6.8, 7.1$, $\theta = 0°\sim45°$, $L = 1\sim12.8, 13.4, 14.0$ in mm.

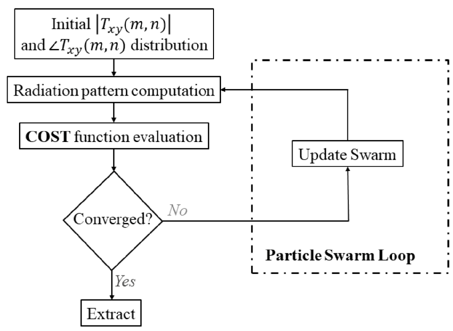

Fig. 2 Flowchart of the optimization loop.

efficient approach is proposed [2]. The approach combines two different techniques as 1-bit phase quantization and phase distribution optimization. The 1-bit element designed is used to introduce phase error to flatten the gain curve of the antenna system. The optimization is performed to not only ensure wideband operation but also minimize the effect of large phase errors caused by 1-bit phase quantization as much as possible. Considering the low-cost fabrication and reduced-complexity of the system design, the proposed approach is a valid alternative for designing wideband transmitarray antennas.

These three aspects are separately discussed in the following.

2. Transmitarray Antennas with Amplitude and Phase Control for Beam-Shaping

An amplitude-phase synthesis method that involves complete transmission coefficient control is developed to design transmitarray antennas with an expected shaped beam, which is composed of two parts, as transmitarray

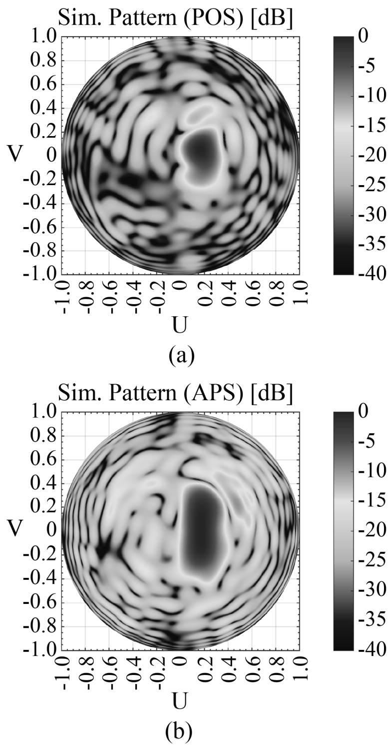

Fig. 3 Simulated Co-Pol radiation patterns (z>0) of (a) POS; (b) APS at 10 GHz.

element design and transmitarray synthesis.

In the process of the transmitarray element design, a three-layer transmitarray element with shaped-dipole structure in the middle layer sandwiched by two orthogonal-positioned grid polarizers is developed and investigated. The detailed schematic of the element is shown in Fig. 1. By turning the dimensions of the shaped-dipole structure (R , L , θ), the proposed transmitarray element achieves full-coverage of complex transmission coefficient. In the process of the transmitarray synthesis, an amplitude-phase synthesis strategy, based on particle swarm algorithm [3], is developed to optimize the element distribution on the transmitarray aperture for required shaped radiation beam. Array factor-based approach is formulated to efficiently compute the radiation pattern, and proper fitness function is defined to implement the optimization loop, which is shown in Fig. 2.

To verify the effectiveness of the method, a $195\text{mm} \times 195\text{mm}$ ($6.5\lambda_0 \times 6.5\lambda_0$ @10GHz) transmitarray antenna with a flat-top radiation pattern is designed, fabricated, and tested. For comparison purpose, the conventional phase-only synthesis method is also implemented by enforcing the transmission amplitude of each element to unity, which can be mainly achieved by fixing the θ of

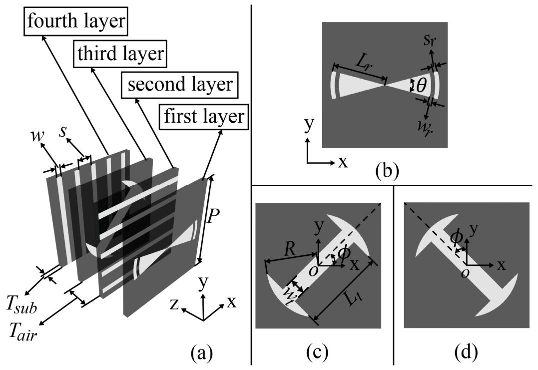

Fig. 4 Unit cell view (a) 3D view; (b) Top view of the first layer; (c) Top view of the third layer; (d) Mirrored structure of the third layer. $s = 2.2$, $w = 0.8$, $T_{air} = 4$, $T_{sub} = 0.8$, $w_t = 2$, $R = 6.2$, $L_t = 1\sim12.2$, $\theta = 30°$, $s_r = 0.5$, $w_r = 0.5$, $L_r = 2\sim7.4$ in mm.

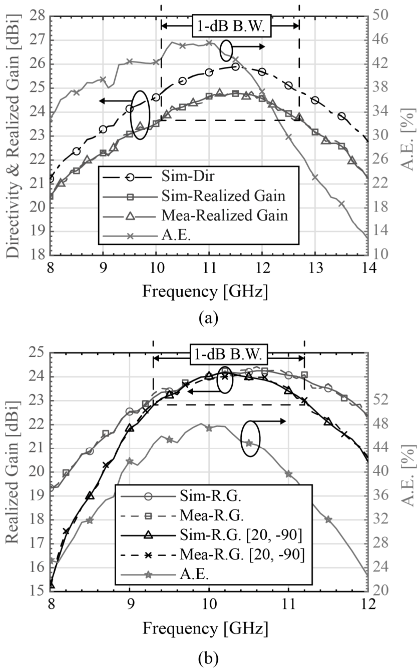

Fig. 5 Gain responses of (a) transmitarray functionality; (b) reflectarray functionality.

each element to 45°. The comparison results of radiation patterns between conventional phase-only synthesis (POS) method and developed amplitude-phase synthesis (APS) method are given in Fig. 3. Compared with the phase-only synthesis method, the developed amplitude-phase synthesis method offers feature of flexible beam-shaping capability and, is a valid alternative to design shaped-beam transmitarray antenna with limited aperture size.

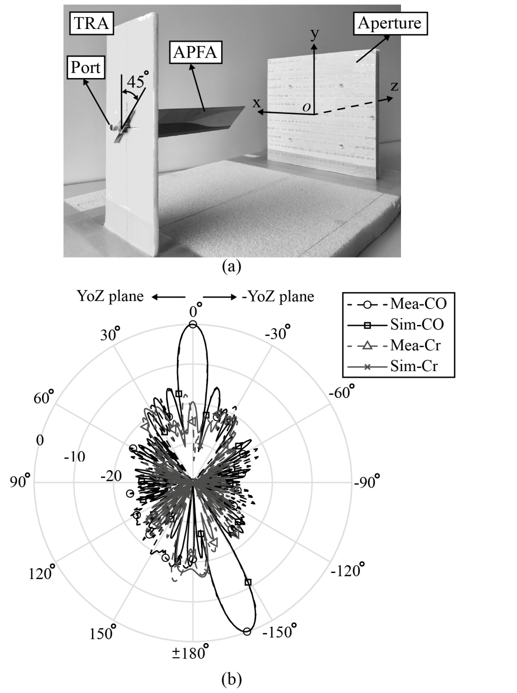

Fig. 6 (a) Photograph of AUT for bidirectional verification; (b) Normalized radiation pattern in YoZ plane at 10 GHz.

3. Transmit-Reflect-Combined-Array Antenna with Forward and Backward Beams

In order to improve the aperture efficiency of single-feed transmit-reflect-combined-array antennas, which is desired in interferometric synthetic aperture radar [4], a novel four-layer polarization-dependent multifunctional element is proposed. The schematic view of the element is shown in Fig. 4. By optimizing the element geometric parameters, the proposed element provides the features of simultaneous and decoupled control of transmission phase and reflection phase, which means the transmission phase is only controlled by varying L_t, while the reflection phase is only controlled by varying L_r. Here, generalized scattering matrix (GSM)-based [5] cascaded network solver is implemented to efficiently evaluate the element performance during the optimization process. The element demonstrates stable oblique-incidence behavior for both transmission and reflection responses. The oblique incidence stability of the element guarantees the high aperture efficiency of the resulting antenna.

Based on the proposed element, a 13×13-element antenna prototype is designed, fabricated, and tested. The antenna operates as transmitarray and reflectarray at the same frequency band by discriminating in polarization of the source feed. The gain responses of transmitarray and reflectarray is shown in Fig. 5 (a) and (b), respectively.

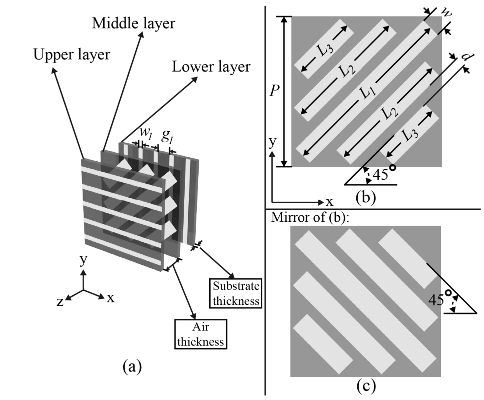

Fig. 7 Unit cell view (a) 3D view; (b) Middle layer of 0-bit element; (c) Middle layer of 1-bit element. $L_1 = 18$, $L_2 = 12.5$, $L_3 = 6.5$, $w = 2$, $d = 1$, $w_1 = 0.8$, $g_1 = 2.2$, $air\_thickness = 4$, $substrate\_thickness = 0.8$ in mm.

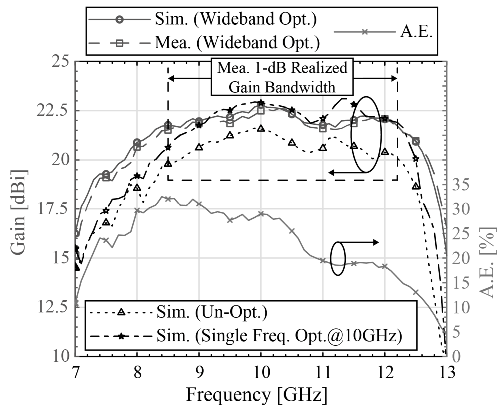

Fig. 8 Gain and aperture efficiency responses.

The measured realized gains of the transmitarray functionality and reflectarray functionality at 10 GHz are 23.5 dBi with 42.2% aperture efficiency and 24 dBi with 47.3% aperture efficiency. Besides, an additional experiment, which is based on slanting the source feed to 45°, is implemented to verify the simultaneously bidirectional capability of the antenna. The photograph and radiation pattern are shown in Fig. 6. Forward and backward beams with equal amplitude can be clearly observed.

4. A Low-Cost and Reduced-Complexity Design Approach for Wideband Transmitarray Antenna

An efficient approach for designing wideband transmitarray antennas, which combines two different techniques as 1-bit phase quantization [6] and phase distribution optimization [7], is proposed. The main advantages of this approach lie in its reduced complexity of the system design and unit cell, the simplicity of the fitness function and optimization loop, and the low-cost fabrication. First, a three-layer polarization-rotation 1-bit element with multiple 45°-positioned parallel strip lines printed in the middle layer is designed and investigated. The schematic of the element is shown in Fig. 7. Here, the element is used to introduce phase error on the transmitarray aperture to balance the gain behavior of the entire system. Then, an optimization is performed to redistribute the phase errors on the aperture at all operating frequency points. It aims to not only ensure wideband performance of the antenna system but also reduce the effect of large phase error caused by the 1-bit phase quantization as much as possible. The underlying core is to shift the elements with large phase error to the edge region, which belongs to the poorly illuminated zone.

To verify the effectiveness of the approach, a 13×17-element ($6.5\lambda_0 \times 8.5\lambda_0$ @10GHz) transmitarray antenna working at 10 GHz is designed, fabricated, and tested. The realized gain responses in different cases are presented in Fig. 8. 1-dB fractional realized gain bandwidth of 37% (8.5-12.2 GHz) is achieved. The approach could be considered as a valid alternative to obtain a wideband behavior of transmitarray antennas.

5. Conclusion

This work covers three different major topics required to be tackled and investigated on transmitarray antennas with enhanced performance and expanded functionalities. Research has been conducted on both unit cell and full transmitarray levels. Several novel designs have been proposed and detailed design procedures have been presented. Some experiments have been performed to validate the designs. Specifically, improved performances, including aperture efficiency, bandwidth, flexibility, and expanded capabilities, including beam-shaping, bidirectional operation, have been achieved.

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