A Generalized Method for Gain Bandwidth Enhancement of Transmitarray Antennas Considering Oblique Incidences

Cai, Yang; Mei, Peng; Lin, Xian Qi; Zhang, Shuai

Published in:
I E E E Transactions on Circuits and Systems. Part 2: Express Briefs

DOI (link to publication from Publisher):
10.1109/TCSII.2023.3297393

Publication date:
2024

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Cai, Y., Mei, P., Lin, X. Q., & Zhang, S. (2024). A Generalized Method for Gain Bandwidth Enhancement of Transmitarray Antennas Considering Oblique Incidences. *I E E E Transactions on Circuits and Systems. Part 2: Express Briefs*, *71*(1), 121-125. Advance online publication. https://doi.org/10.1109/TCSII.2023.3297393

A Generalized Method for Gain Bandwidth Enhancement of Transmitarray Antennas Considering Oblique Incidences

Yang Cai, *Student Member, IEEE*, Peng Mei, *Member, IEEE*, Xian Qi Lin, *Senior Member, IEEE*, and Shuai Zhang, *Senior Member, IEEE*

***Abstract*—This paper introduces a generalized phase compensation method to enhance gain, 1-dB gain bandwidth of transmitarrays considering oblique incidences. This method is based on studying the transmission phase of each element in the holistic framework of a transmitarray, where all oblique incidences to each element are included. As a result, the actual transmission phase of every element at different spatial positions involving oblique incidence effects can be obtained, which is leveraged to improve the performance of transmitarrays. The proposed method is especially efficient for transmitarrays with discrete phase states. For proof of the concept, dielectric lenses with a 2-bit phase quantization are configured to demonstrate performance enhancement. The simulated results show that the gain enhancement of 1.67 dB, 3.41 dB, and 4.5 dB at 26 GHz can be achieved when the focal length-to-diameter ratio (F/D) is 0.37, 0.24, and 0.14, respectively, which are experimentally verified by the measured results.**

***Index Terms*—Transmitarrays, dielectric lens, phase compensation, oblique incidences.**

I. Introduction

Transmitarray antennas (TAs), typically consisting of a feed source and phase-shifting surfaces, have been extensively investigated in recent years owing to their various advantages such as lightweight, low-cost, and reconfigurability compared to conventional phased arrays [1]. The phase-shifting surfaces can convert the spherical waves radiating from the feed source to plane waves, therefore, achieving a high gain. Phase-tuning elements are fundamental parts to form the phase-shifting surfaces of a transmitarray antenna, which can be implemented by frequency selective surfaces (FSSs) [2]–[5] and dielectric lenses [6]–[9]. According to the configuration of a TA, the electromagnetic waves radiating from the feed source do not always impinge on each element of the phase-shifting surfaces normally due to the spatial location of each element with respect to the feed source. The frequency responses of elements are sometimes qualitatively examined by checking the phase stability under oblique incidences and polarizations in the literature to estimate the oblique incidence effects. However, the oblique incidence effects are not compensated for to enhance the performance of transmitarray antennas since the compensations are complicated and challenging.

Some methods have been recently developed to reduce the impacts of oblique incidences to improve the performance of reflectarray or transmitarray antennas [3], [10]-[13]. In [12], [13], elements were still simulated with periodic boundary conditions (PBCs), while plane waves involving all possible incidence angles and polarizations were added to establish a database containing the effects of oblique incidences. Nevertheless, it is still cumbersome and needs enormous simulation data to calibrate phase errors. Another method to reduce oblique incidence effects is to optimize the extra phase reference imposed on each element of reflectarray or transmitarray antennas [14], [15]. Since different elements at the same position in the phase-shifting surfaces have distinct responses to oblique incidences, it is feasible to optimize the phase reference of each element to compensate for the oblique incidence effects. However, the improvements of this method on reflectarray and transmitarray antennas are rather limited, and the procedure is also time-consuming.

In this paper, a generalized method considering oblique incidence effects is proposed and studied to enhance the gain and 1-dB gain bandwidth of transmitarray antennas. The element arrays are proposed to derive and extract the accurate transmission phase of each element at different spatial positions involving oblique incidences (both angles and polarizations). The accurate transmission phases are then leveraged to implement a transmitarray antenna with enhanced performance. The proposed method also outperforms the conventional solutions [10]-[15] significantly in terms of simulation time. To validate the effectiveness of the proposed method, several transmitarray antennas based on 2-bit dielectric lenses are designed and compared. Based on the derived actual

This work was supported in part by China Scholarship Council (CSC) and in part by innovationsfonden project of MARS2. (*Corresponding author: Peng Mei.*)

Y. Cai, P. Mei and S. Zhang are with the Antennas, Propagation and Millimeter-Wave Systems Section, Department of Electronic Systems, Aalborg University, 9220 Aalborg, Denmark (e-mail: yangc@es.aau.dk, mei@es.aau.dk, sz@es.aau.dk).

X. Q. Lin are with the School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China, and also with the Yangtze Delta Region Institute (Huzhou), University of Electronic Science and Technology of China, Huzhou 313001, P. R. China. (e-mail: xqlin@uestc.edu.cn).

transmission phases of elements from the element arrays, the transmitarray antenna based on the proposed method can exhibit a higher gain and wider 1-dB gain bandwidth. Most importantly, when the focal length-to-diameter ratio (F/D) of the transmitarray antenna is smaller where the oblique incidence effects are much stronger, the gain improvement is more notable accordingly. This method can keep the aperture efficiency of a transmitarray antenna with a reduced F/D, which is promising for compact requirements for millimeter-wave wireless communications.

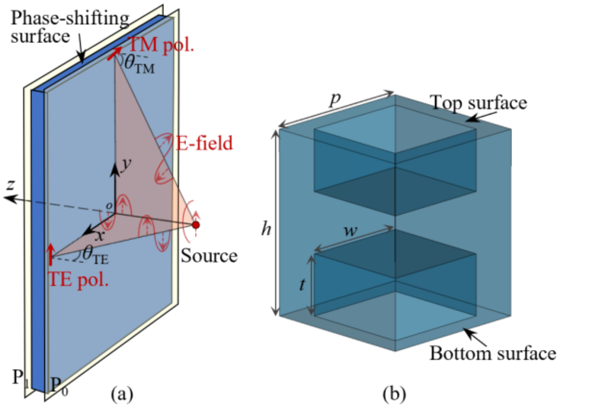


Fig. 1 (a) Configuration of the TA, (b) dielectric lens element for phase tuning.

II. Principle and Methodology

A. The effects of oblique incidences

For transmitarray antennas, the spherical waves radiating from the feed source impinge on the phase-shifting surfaces. When the elements provide desired phase shifts to compensate for the spatial path differences from the feed source to the elements, the transmitarray antennas can achieve a high gain and even tilted beams [16]. It should be noted here that all elements are not always illuminated with normal incidence waves, and elements at different spatial positions within the phase-shifting surfaces are sometimes illuminated with various oblique incidence angles and polarizations as can be seen in Fig. 1(a). Moreover, the same element at different positions within the phase-shifting surfaces usually demonstrates distinct frequency responses due to the effects of oblique incidences on the element (oblique incidence angles are different). If we do not consider the oblique incidence effects and only compensate for the phase shift of each element based on the frequency response under normal incidence, the performance of the corresponding TA would be degraded due to the pronounced phase errors introduced by oblique incidences.

B. Element array and actual phase response extraction.

In order to diminish the aforementioned oblique incidence effects for reflectarray and transmitarray antennas, it is critical to obtain the actual phase response of each element in which all oblique incidence effects are taken into account. As mentioned before, the solutions reported in [12],[13] are not efficient to reduce or remove the oblique incidence effects. Here, we construct element arrays (EAs) that consist of identical elements and simulate them in the real array environment to monitor the phases on two well-defined observation planes. As a result, the actual phase response of each element at different spatial positions of the EA can then be extracted by subtracting the phases on the observation planes. Specifically speaking, as illustrated in Fig. 1(a), the incident reference plane is P_0 and the outgoing reference plane is P_1 which are planes on or close to the two surfaces of the phase-shifting surfaces. In the case of phase tunning elements with varying heights, the two reference planes are the top and bottom surface planes of the highest element as shown in Fig.1(b). The actual phase shift of each element in the real array environment is the phase difference between the reference planes P_1 and P_0. If the phase-shifting surfaces of a transmitarray antenna are implemented by elements with a phase quantization of M-bit ($360/2^M$ °), the total required amount of phase states is 2^M. In this case, we only need to figure out the actual phase shift of each phase state at different spatial positions in the real array environment, which can be extracted and obtained by simulating the EAs built by elements of each phase state. It should also be noted that the proposed method reduces the total simulation times of an M-bit TA with N×N elements to 2^M. By contrast, the times of simulating elements with PBCs are at least $2^M \times N^2/4$ because there are at least $N^2/4$ different combinations of incidence angles and polarizations for the elements. The extracted actual phase shifts of different elements in a real array environment are then fully leveraged to implement a transmitarray antenna, aiming at enhancing the performance (e.g., higher gain, bandwidth, and higher aperture efficiency, etc.) as the oblique incidence effects are significantly reduced or even removed.

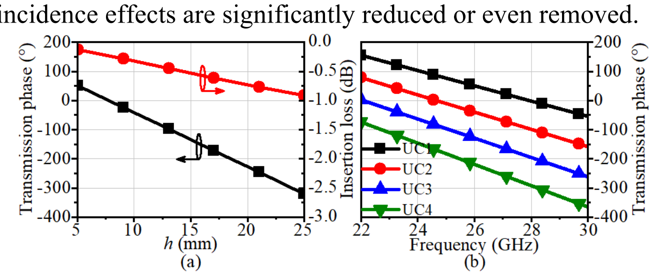


Fig. 2 (a) Transmission phase and insertion loss of the element with respect to height *h*, (b) Transmission phase of the 2-bit (4 states) elements.

III. Implementation of the Element Array and Transmitarray

To verify the effectiveness of the proposed method, three transmitarray antennas based on dielectric lenses are designed in this section and compared to the ones without considering oblique incidences. As stated in Section II, the complexity and simulation workload of the proposed method is closely related to the phase quantization used in the transmitarray antenna design. As a result, a 2-bit phase quantization is adopted here for simplicity.

A. Design of the unit cell

The element used in this paper is a dielectric-based stub as shown in Fig. 1(b) due to its simplicity and ease of fabrication [6]. On the other hand, this kind of element possesses significant oblique incidence effects, which would sufficiently demonstrate the superiority of the proposed method. To minimize the reflection at the interfaces of the dielectric stub and air, two antireflection (AR) structures are introduced by partially drilling a hole on two ends of the dielectric stub, which tunes the effective permittivity of the transition part to reduce impedance mismatch [7]. The dimensions of the element are p = 5 mm, w = 3.5 mm, and t = 2 mm. Using traditional PBCs to simulate the elements under normal incidence, the transmission phase response and insertion loss versus element length h at 26 GHz are obtained as displayed in Fig. 2(a). According to the phase relation in Fig. 2(a), four elements are selected with the length of 5.1 mm, 9.9 mm, 14.7 mm, and 19.5 mm corresponding to a phase shift of 50.4°, -39.8°, -129.2°, and -219.2°, respectively, which achieves a 2-bit phase quantization at 26 GHz as shown in Fig. 2(b).

B. Extraction of the actual phase response

Four corresponding EAs of these four elements are then constructed with an aperture of 100 mm × 100 mm. The EAs are center fed by a linearly polarized horn antenna at an optimum F/D of 0.37 based on the $\cos^q$ model [17].

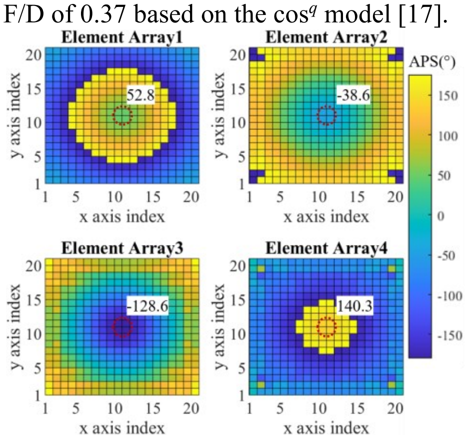


Fig. 3 Extracted actual phase shift values of four designed EAs.

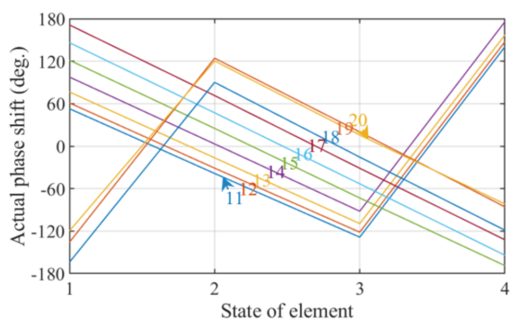


Fig. 4 Actual phase relations at some of the positions (index: y = 11, x = 11-20).

As displayed in Fig. 1(a), the co-polarization of the E-field (E_y-component) on the incident reference plane (z = 0 mm) and the outgoing reference plane (z = 19.5 mm, i.e., the surface planes of the highest element) are extracted. The actual phase shift of each element at different positions in the real array environment is then calculated at 26 GHz by subtracting the phases of the E_y-component on these two reference planes. The actual phase shift (APS) of each element of these four EAs at different positions are then illustrated in Fig. 3, where it is observed that the APSs of elements at the center positions of the EAs are quite similar to the results obtained from a unit cell simulation with PBCs under normal incidence. Nonetheless, as elements locate away from the center position gradually, a notable phase difference between the EA's and UC's results is observed, which is attributed to the oblique incidence effects. According to the APS values in Fig. 3, the actual phase relations in a real array environment are obtained, and the relations of elements along the center column are plotted in Fig. 4 for the sake of brevity. Compared to the unit cell simulation with PBCs, the proposed method stands out with a smaller number of simulation models as well as less simulation time when the phase quantization is 1- or 2-bit. In this design, it takes 200 minutes and 12 minutes to obtain all the desired phase responses by simulating unit cells with PBCs and element arrays, respectively.

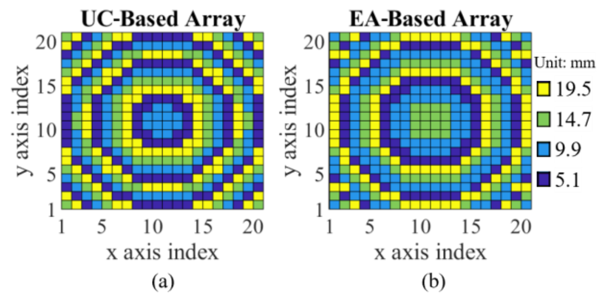


Fig. 5 Configurations of the (a) UC-based TA and (b) EA-based TA.

C. Implementation of the transmitarray antenna based on the dielectric lens.

The transmitarray antenna using the actual phase response from EAs' simulation (denoted as EA-based TA) is designed by compensating for the required phase of each element located at position (m, n) in the array with the actual phase relation at position (m, n). Another transmitarray antenna with the same F/D of 0.37 is designed without considering the oblique incidence effects by using the phase response of UC under normal incidence (denoted as UC-based TA) for comparison. Fig. 5 shows the configurations of two transmitarrays with 20 × 20 elements. The realized gains of two transmitarray antennas are simulated and shown in Fig. 6. The realized gain is enhanced from 22-28 GHz, but the realized gain drops at high frequencies due to the phase error from the following two parts: One part is the phase quantization error resulting from the inaccuracy of the 2-bit phase quantization as can be observed in Fig. 2 (b) that the phase difference among four states is no longer 90°; the other part is the frequency-dependent free space path propagation phase error, i.e., spatial dispersion. The phase difference between two elements in an array is calculated as

$$\Delta\varphi = \varphi_j - \varphi_i = k_0 \times (R_j - R_i) \quad (1)$$

where k_0 is the wavenumber in free space, R_j and R_i are the distance from the phase center of the feed source to the elements j and i. As the frequency goes higher, the required phase difference between elements increases according to (1), which indicates the phase distribution varies more rapidly at higher frequencies. Hence, the elements should change rapidly accordingly to achieve the required phase compensation. However, at the frequency of interest, extra phase shifts are introduced for the same element with the effects of oblique incidences considered as shown in Fig. 3 (either using the method in the literature [12] or the proposed one in this paper).

Consequently, it requires less variation in element height or size to achieve the desired phase distribution, which goes against the requirement for a distribution where elements change rapidly at higher frequencies. Conversely, the required phase distribution changes gradually at lower frequencies, resulting in a distribution with fewer element variations in height or size. As a result, considering the oblique incidence effects at center frequency leads to better phase compensation at lower frequencies and worse compensation at higher frequencies. Eventually, the realized gain enhances more significantly at lower frequencies while remaining at higher frequencies. A flat gain curve within the operating bandwidth can be obtained, and the 1-dB gain bandwidth is therefore broadened.

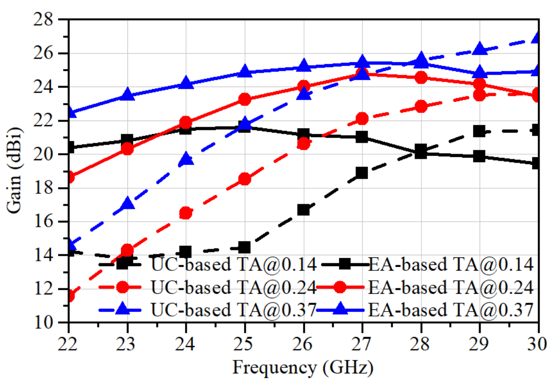
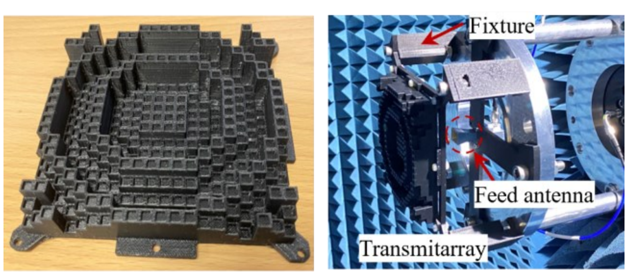


Fig. 6 (a) Simulated gain of UC and EA-based TA with different F/D.

TABLE I: SIMULATED GAINS OF THREE TAS

F/D	UC-based TA Gain@26GHz(dBi)	EA-based TA Gain@26GHz(dBi)	Enhancement (dB)
0.14	16.66	21.16	4.5
0.24	20.61	24.02	3.41
0.37	23.50	25.17	1.67

The corresponding feeding distance is 20mm, 34mm, and 52mm, respectively.



(a) (b)

Fig. 7 (a) Prototype of the EA-based TA, (b) Setup of the measurement.

Furthermore, transmitarray antennas with different F/D are also studied with the array size fixed. The distance between the feed source and the dielectric lens is shortened to 34 mm and 20 mm corresponding to an F/D of 0.24 and 0.14. The EAs with different F/D are implemented and re-simulated to extract the actual phase response, and two groups of corresponding TAs are then constructed. It can be predicted that the transmitarray with a smaller F/D will have a lower realized gain but lead to a larger gain enhancement as a smaller F/D suffers from much stronger oblique incidence effects. Fig. 6 shows the realized gains of three groups of transmitarray antennas with different F/D, where it is clearly observed that the gains of EA-based TAs are always better than those of UC-based ones from 22-28 GHz. As can be seen in Table I, a more notable gain enhancement can be achieved with a smaller F/D, which is highly consistent with the prediction and principle of the proposed method. Besides, EA-based transmitarray antennas achieve a higher gain even with a smaller F/D compared to the UC-based ones, which is promising to fulfill the low-profile requirements of transmitarray antenna designs for space applications. The aperture efficiency of the EA-based transmitarray with an F/D of 0.37 is 34.2% which is acceptable since a 2-bit phase quantization typically introduces some phase errors and the F/D is relatively small as well.

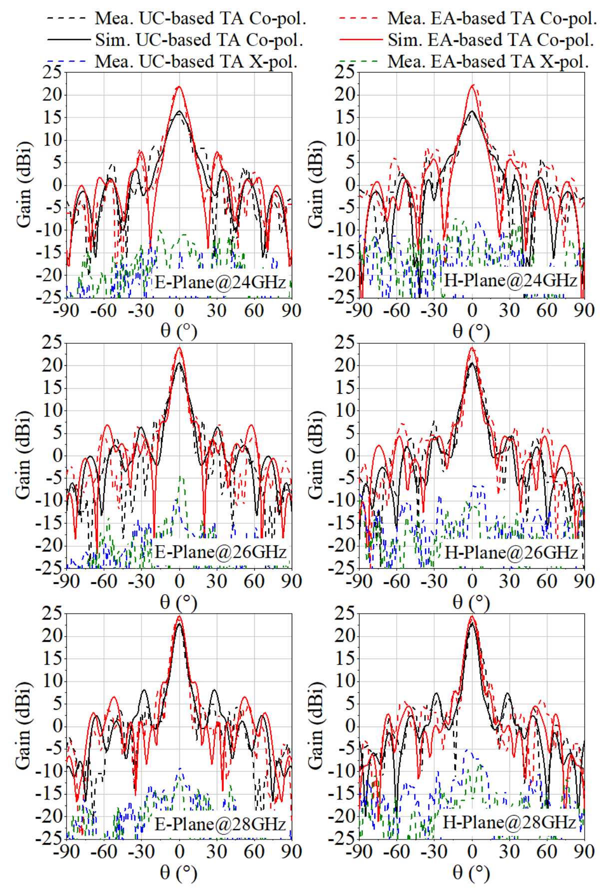


Fig. 8 Measured and simulated radiation patterns in E- and H-planes at 24GHz, 26GHz, and 28 GHz.

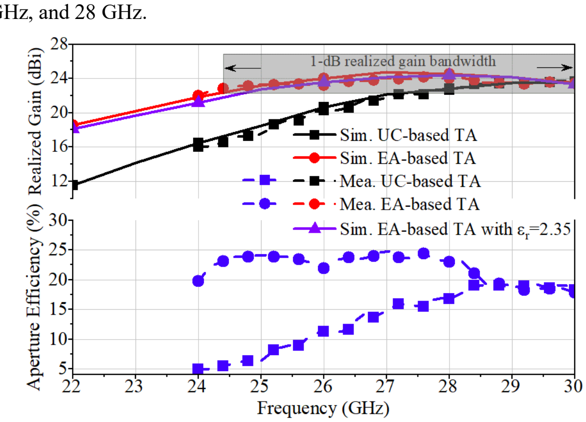


Fig. 9 Comparison of the measured realized gain and aperture efficiency with simulated ones.

IV. Experimental Verifications

Two prototypes of transmitarrays of 100 mm × 100 mm are manufactured using a 3-D printer with the filament of acrylonitrile butadiene styrene (ABS) plastic (ε_r = 2.55, tanδ = 0.01), and the fixtures are all made of ABS as well. The accuracy of the 3-D printer used in this paper is 0.0125 mm, 0.0125 mm, and 0.01 mm along *x*-, *y*-, and *z*-direction respectively. The EA-based one is shown in Fig. 7(a). The transmitarray is center fed by a horn antenna with an F/D of 0.24. The measurement setup is displayed in Fig. 7(b).

The measured radiation patterns in both E- and H-planes at 24 GHz, 26 GHz, and 28 GHz are illustrated in Fig. 8, which shows good coherences to the simulation results. The measured cross polarizations are all below -25 dB. The measured realized gain also agrees well with the simulated ones, as plotted in Fig. 9. A little deviation is observed for the EA-based TA, which owes to the fabrication tolerance of the dielectric lens. When the relative permittivity of the dielectric lens is 2.35, the simulation and measurement results match well. The measured 1-dB bandwidth is 19.2% which is significantly enhanced compared to the UC-based TA. The aperture efficiency is also plotted in Fig. 9, from which a significant improvement is observed after compensating for the oblique incidence effects. A comparison between the proposed TA and some other TAs in the literature is listed in Table II. The proposed transmitarray achieves high aperture efficiency and wide 1-dB gain bandwidth with a reduced F/D and low design complexity.

TABLE II: Comparison of Different Transmitarrays

Ref.	Freq. (GHz)	F/D	1-dB Gain BW (%)	Aperture Efficiency (%)	Oblique Effect Included	Design Complexity
[9]†	30	1	21.5	38.6	No	Low
[18]※	29	0.67	15.8 (3dB)	15.4	No	Low
[12]†	12	0.2	6	33	Yes	High
[13]†	30	0.5	8.5	61.9 (ideal)	Yes*	High
This Work※	**26**	**0.14** **0.24** **0.37**	**16** **19.2** **18.2**	**16.2** **21.9** **34.2**	**Yes**	**Low**

* Only TM polarization is considered, † Continues phase, ※ 2-bit quantization phase

V. Conclusion

This paper presents a generalized design method to compensate for the phase errors introduced by oblique incidence effects to enhance the performance of transmitarray antennas. The element arrays are proposed to extract the actual phase relations of each element at each specific position in the real array environment. The realized gain at lower frequencies is significantly improved with a wider 1-dB gain bandwidth compared to the array without considering oblique incidence effects. The proposed method outperforms the existing works in the implementation of transmitarray antennas when it comes to discrete phase quantization, which can also be applied to reconfigurable intelligent surfaces (RISs) that are typically implemented with elements of 1-bit or 2-bit phase quantization to enhance the performance.

References

[1] S. Shi et al., “Wideband Planar Phased Array Antenna Based on Artificial Magnetic Conductor Surface,” *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 67, no. 10, pp. 1909–1913, Oct. 2020.

[2] B. D. Nguyen and C. Pichot, “Unit-Cell Loaded With PIN Diodes for 1-Bit Linearly Polarized Reconfigurable Transmitarrays,” *IEEE Antennas Wireless Propag. Lett.*, vol. 18, no. 1, pp. 98–102, Jan. 2019.

[3] C.-Y. Hsu, L.-T. Hwang, T.-S. Horng, S.-M. Wang, F.-S. Chang, and C. N. Dorny, “Transmitarray Design With Enhanced Aperture Efficiency Using Small Frequency Selective Surface Cells and Discrete Jones Matrix Analysis,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 8, pp. 3983–3994, Aug. 2018.

[4] H. Nematollahi, J.-J. Laurin, J. E. Page, and J. A. Encinar, “Design of Broadband Transmitarray Unit Cells With Comparative Study of Different Numbers of Layers,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1473–1481, Apr. 2015.

[5] P.-Y. Feng, S.-W. Qu, S. Yang, L. Shen, and J. Zhao, “Ku-Band Transmitarrays With Improved Feed Mechanism,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 2883–2891, Jun. 2018.

[6] P. Nayeri et al., “3D printed dielectric reflectarrays: Low-cost high-gain antennas at sub-millimeter waves,” *IEEE Trans. Antennas Propag.*, vol. 62, no. 4, pp. 2000–2008, 2014.

[7] H. Yi, S. W. Qu, K. B. Ng, C. H. Chan, and X. Bai, “3-D Printed Millimeter-Wave and Terahertz Lenses with Fixed and Frequency Scanned Beam,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 2, pp. 442–449, Feb. 2016.

[8] P. Mei, S. Zhang, Y. Cai, X. Q. Lin, and G. F. Pedersen, “A reflectarray antenna designed with gain filtering and low-RCS properties,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 8, pp. 5362–5371, Aug. 2019.

[9] A. Massaccesi et al., “3D-Printable Dielectric Transmitarray with Enhanced Bandwidth at Millimeter-Waves,” *IEEE Access*, vol. 6, pp. 46407–46418, Aug. 2018.

[10] F. Venneri, S. Costanzo, G. di Massa, and G. Angiulli, “An improved synthesis algorithm for reflectarrays design,” *IEEE Antennas Wireless Propag. Lett.*, vol. 4, no. 1, pp. 258–261, 2005.

[11] M. Arrebola, J. A. Encinar, and M. Barba, “Multifed printed reflectarray with three simultaneous shaped beams for LMDS central station antenna,” *IEEE Trans. Antennas Propag.*, vol. 56, no. 6, pp. 1518–1527, Jun. 2008.

[12] G. B. Wu, S. W. Qu, C. Ma, S. Yang, and C. H. Chan, “Reflectarray antenna design with arbitrary incident and reflection beam angle,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 11, pp. 5964–5973, Nov. 2018.

[13] E. R. F. Almajali and D. A. McNamara, “Angle of Incidence Effects in Reflectarray Antenna Design: Making gain increases possible by including incidence angle effects,” *IEEE Antennas Propag. Mag.*, vol. 58, no. 5, pp. 52–64, Oct. 2016.

[14] A. H. Abdelrahman, P. Nayeri, A. Z. Elsherbeni, and F. Yang, “Bandwidth Improvement Methods of Transmitarray Antennas,” *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 2946–2954, Jul. 2015.

[15] H. Yang et al., “A 1-Bit 10 × 10 Reconfigurable Reflectarray Antenna: Design, Optimization, and Experiment,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2246–2254, Jun. 2016.

[16] P. Nayeri, F. Yang, and A. Z. Elsherbeni, Reflectarray antennas: theory, designs and applications. Hoboken, NJ, USA: Wiley, 2018.

[17] A. Yu, F. Yang, A. Z. Elsherbeni, J. Huang, and Y. Rahmat-Samii, “Aperture efficiency analysis of reflectarray antennas,” *Microw. Opt. Technol. Lett.*, vol. 52, no. 2, pp. 364–372, Feb. 2010.

[18] F. Diaby, A. Clemente, R. Sauleau, K. T. Pham, and L. Dussopt, “2 Bit Reconfigurable Unit-Cell and Electronically Steerable Transmitarray at Ka -Band,” *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 5003–5008, Jun. 2020.