Novel one-bit digital coding broadband transmitarray antenna

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Abstract In this paper, a novel broadband transmitarray (TA) design based on one-bit digital coding. The double-layer transmitarray element is composed of a notched square ring patches which is etched the upper layer of the dielectric substrate, and the lower layer is the same metal slit having the same shape as the notched square ring patch, but the notch direction is rotated by 180°. By changing the physical dimensions of the notched square ring element, a phase coverage of about 360° can be achieved. To realize the coding transmitarray, the phase compensation is fuzzified. Two kinds of elements with 0 and π phase responses to represent “0” and “1” elements for 1-bit digital coding are introduced. Theoretical rules of phase compensation fuzzified and a broadband transmitarray antenna are designed by coding unit cell. We design, manufacture and measure a digital coding transmitarray antenna by using the proposed element. The measured results show that the transmitarray has the 1-dB gain bandwidth of 25% (8.4 GHz - 10.8 GHz). The proposed digital coding transmitarray antenna has a wide gain bandwidth. The measured results agree with the simulated results well, which verifies the feasibility and correctness of the proposed structure.

Keywords: broadband, 1-bit digital coding, transmitarray, fuzzy phase synthesis

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

In recent years, broadband wireless systems have become more and more attractive for the development of high-speed communication radio links. Antennas are indispensable core devices in modern wireless communication systems, and their performance requirements are also increasing. Among the possible antenna solutions, the planar transmitarray technique has received more and more attention because of its advantages such as high efficiency, high gain, low profile, light weight and easy manufacturing, etc. However, narrow bandwidth is one major shortcoming of the transmitarray [1, 2, 3, 4, 5, 6].

Recently, research on broadband transmitarray antenna has been proposed. However, the development of broadband transmitarray antenna is still in its infancy. In [1], a TA antenna composed ultrathin slot unit is presented. The related elements consist of two thin dielectric layers superimposed on each other, and the annular ring slots is placed

on the outer layers and on the interface is a PBG unit. The 1-dB gain bandwidth at center frequency is 5.7% of the TA. In [2], an X-band circularly polarized low-profile TA is implemented by using dual-linearly polarized unit. From the measurement, the axial-ratio and 1-dB gain bandwidth are 3.5% (9.8–10.15 GHz) and 4% (9.7–10.1 GHz), respectively. The maximum gain is 21.9 dBi at 10 GHz. In [3], The unit cell which is a modified Malta crosses printed on a dielectric substrate is applied to design a TA. From the measurement, The gain and 1-dB gain bandwidth are 33.0 dBi and 5.9% at 20 GHz, respectively.

Because of high Q value of resonant units and spatial differential phase delay, the narrow-band is the main shortcoming of the TA. The spatial differential phase delay comes from the different path lengths between the feed and each TA unit [7]. Up-to-date broadband transmitarray designs are realized mainly using three approaches. Delay lines with variable length is used to compensate phase is the first one [8]. Stacked patches with variable parameters is the second one [9]. By using multi-resonance mode at neighboring frequencies to generating a wide bandwidth is the third one [10].

Capasso built the general reflection and refraction law in 2011, which is the theoretical foundation of metasurface [11]. Because of the interfaces and drastically change the flow of reflected and refracted light, phase discontinuities for light propagation is produced by special nanoantenna-array metasurfaces. Giovampaola and Engheta first proposed digital metamaterials. They are inspired by digital electronics and design metamaterials by using two “metamaterial bits” as building blocks [12]. Then, Cui et al. presented coding metamaterials that are composed of only two kinds of elements with 0 and π phase responses, which are named as “0” and “1” elements. By coding “0” and “1” elements with controlled sequences (i.e., 1-bit coding), electromagnetic (EM) waves can be manipulated and realized different functionalities [13]. By using fuzzy phase control a novel 1-bit digital coding broadband reflectarray design method proposed by Li et al. [14]. The studies of metamaterial antennas are reported in [15, 16, 17, 18, 19]. Another relative research are proposed by [20, 21, 22, 23, 24].

Based on a notched square ring structure, a novel design approach for 1-bit digital coding broadband transmitarray is proposed in this paper. The element proposed here composed two metallic layers, which has a wide transmission band width. Compared to [25] and [26], the layer is 1 and 2 less, respectively. The substrate is only 3 mm (0.03λ , λ is the wavelength at 10 GHz), which is 30% and 23% thinner than the transmitarrays proposed in [27] and [28], so the size

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of TA is very small at 10GHz. A 30×30 low-profile TA which is designed by using the element proposed here is easy to be fabricated. Compared to the simulated response, the measured one shows the validation of the TA. A broadband performance can be achieved by proposed TA with 1-bit digital coding scheme, whose 1-dB gain bandwidth is 25% (8.4 GHz - 10.8 GHz).

The rest of the letter is organized as follows. We introduce the fundamentals of design methods in Section II. In Sections III, the simulation results of the transmitarray composed of the proposed element are presented. Section IV, presents the measured results of the transmitarray composed of the proposed element. Section V gives the conclusions of this paper.

2. Fundamentals of design methods

According to the configuration of a typical transmitarray, each array element can be compensated by appropriate phase to form the ideal main beam in the desired orientation. The number of elements of the array antenna covered by the electromagnetic wave emitted by the feed horn at the $\vec{r}_f$ is $m \times n$, as shown in Fig. 1, the sum of the illumination fields of all the elements in any direction can be expressed by the following formula:

$$\vec{E}(\hat{u}) = \sum_{m=1}^M \sum_{n=1}^N F(\vec{r}_{mn} \cdot \vec{r}_f) A(\vec{r}_{mn} \cdot \hat{u}_0) A(\hat{u}_0 \cdot \hat{u}) \cdot \exp \{ -jk_0 [|\vec{r}_{mn} - \vec{r}_f| - \vec{r}_{mn} \cdot \hat{u}] + j\varphi_c \} \quad (1)$$

Where A is the element radiation direction. F is the radiation direction function of the feed. $\vec{r}_{mn}$ is a vector for the position of the mn -th radiation element. The vector of the mn -th element geometric center from the feed's phase center is $\vec{r}_f$. The compensation phase of each element is φ_c . The direction of the main beam is $\hat{u}_0$. Because of phase accumulated traveling between the feed horn and the transmitarray surface, the amount of phase adjustment needed at each antenna element depends on the phase delay an incident ray. From [29], the relative compensation value at each element is given by (2):

$$\varphi_c = -k_0 (|\vec{r}_f| + \vec{r}_m \cdot \hat{u}_0) + 2n\pi, \quad n = 1, 2, 3, \dots \quad (2)$$

k_0 is the propagation constant.

First, in order to determine the 1-bit coding transmitarray antenna, the important key is the designing method of “0”

Fig. 1 Phase delay path diagram of the microstrip transmitarray antenna.

and “ π ” elements. In this letter, a printed notched square metallic patch is chosen as the transmission element, as shown in Fig. 2. Fig. 2 (a) is the top view of element, Fig. 2 (b) is the bottom view of element of the array element and the square ring notch angle of the two elements is 180° , Fig. 2 (c) is the side view of the element, dielectric constant is 2.65, and the dielectric substrate thickness $h = 1$ mm, the array element period a is 7 mm. The transmitarray element realizes different phase compensation by changing the gap size of the ring (the size of the arm length d in Fig. 2). The band in the design is in the sub-wavelength band, so the period is about one-third of λ (λ is the wavelength at 10 GHz). By selecting an appropriate element structure and size, the antenna element period can be effectively reduced. The element model is simulated using periodic boundary conditions, which is shown in Fig. 3. The phase-length curve can be calculated by analyzing the infinite periodic array of identical microstrip elements [30].

For the digital transmitarray design, the other key is how to digitize the compensation phase obtained by the expression (2) by “0” and “1”. To simplify the design, we use 1-Bit digitization method, that is, let the array elements representing the two numbers of “0” and “1” correspond to the

Fig. 2 Notched square element the parameters of element.

Fig. 3 Infinite periodic model of the notched square element at normal incidence.

Fig. 4 Phase characteristics of the element transmission coefficients.

Fig. 5 Transmission phase of the element at different frequencies.

Fig. 6 Transmission magnitude of the element transmission coefficients.

transmission phases of “0” and “ π ” respectively, as follows:

$$\varphi_c|_{1\text{-Bit}} = \begin{cases} 0, & -\pi/2 < \varphi_c < \pi/2 \\ \pi, & \pi/2 < \varphi_c < \pi \text{ and } -\pi < \varphi_c < -\pi/2 \end{cases} \quad (3)$$

Where $\varphi_c|_{1\text{-Bit}}$ represents a one-bit digitized compensation phase. By the formula (2), we can obtain the compensation phase of each array element, and then classify the compensation phase by equation (3). When φ_c is greater than $-\pi/2$ and less than $\pi/2$, the element is “0” array element. When φ_c is greater than $\pi/2$ and less than π or greater than $-\pi$ and less than $-\pi/2$, the element is “1” array element. The purpose of digital coding is to realize phase compensation and make the far-field electric field superposition in the same direction, so as to obtain the ideal beam pattern. Fig. 4 shows the transmission characteristic of the array element. From

Fig. 7 Resonance characteristics of the element transmission coefficients.

Table I Design parameters of the transmitarray element

Parameter	“0” Element Value	“1” Element Value
a	7mm	7mm
l	5mm	5mm
w	0.5mm	0.5mm
d	2mm	3.2mm
h	1mm	1mm
ε_r	2.65	2.65
δ	0.0001	0.0001

the phase curve in Fig. 4, the dimensions corresponding to “0” array element and “1” element can be obtained. The size of d (element length) in the “0” array element is about 2mm, and the corresponding compensation phase is about 0° , the d dimension of the “1” array element is about 3.2mm, and the corresponding compensation phase is 180° . Fig. 5 is the transmission phase curves of the element at different frequencies. As shown in this figure, the transmission phase curves of the element are approximately parallel over a large frequency band. Therefore, the proposed element has broadband characteristic. Fig. 6 shows transmission magnitude of the element transmission coefficients. Fig. 7 shows the resonance characteristics of the element. The detailed parameters of the coverage of the 360° phase offset and the better linearity of element are given in Table I.

3. Transmitarray simulation

In this chapter, the digital planar transmitarray antenna is designed as a 30×30 array, the substrate thickness is 1mm, the top layer is a notched square ring structure array element patch, and the bottom layer is a notched square ring gap structure and the array element is two layers. The square ring notch angle of the element differs by 180° . The phase distribution of the TA is shown in Figure 8. The simulation model and size of the array in HFSS are shown in Fig. 9. The feed radiates from the xoy plane to the front surface, and its incident angle is $(\theta_i, \varphi_i) = (0^\circ, 0^\circ)$, that is, directly above the geometric center of the front, the main beam direction of the transmitted through the plane is on the xoy plane, and the main beam angle is $(\theta_r, \varphi_r) = (0^\circ, 0^\circ)$, that is, vertical front plane emission.

In order to obtain the desired phase shift curve, in the process of designing the transmitarray, each element size or rotation angle in the array must be adjusted. This compensated phase shift curve can be obtained by full-wave

simulation of infinite period boundary conditions.

In the design of this chapter, in order to reduce the element size and the coupling between the elements, we use the element size of the more linear region in the phase length curve as much as possible. Fig. 10 shows the simulation pattern of the three frequencies of 8 GHz, 10 GHz and 11 GHz in the xoy plane. As can be seen from this figure, the 1-Bit digital transmitarray has better directivity in its frequency band. The peak gain of the simulation at a center frequency of 10GHz is 22.41dB. However, the 1-Bit digital transmitarray still has some shortcomings, such as its higher flap and lower gain. The main reason is that the digital transmitarray of 1-Bit has a large degree of blurring of the compensation phase. If the gain is to be increased, the low direct side level, the most direct and effective idea is to increase the bit rate, like using a two-bit or higher design

Fig. 8 The phase distribution of proposed TA.

Fig. 9 30 × 30 DCR transmitarray simulation model.

Fig. 10 The simulated transmitarray radiation gains at 8 GHz, 10GHz and 11GHz.

method. Due to the fuzzification of the compensation phase, it is divided into two parts, corresponding to only two types of elements. The elements in the array do not have precise phase compensation, so the gain of the transmitarray is low.

4. Transmitarray experiment verification

From the simulation analysis in the previous section, the transmitarray with 1-bit digital coding was manufactured and measured. Fig. 11 shows the proposed array. The array and element prototype of this sample correspond to Fig. 9. The measured system is shown in Fig. 12. TA antennas are vertical the same as TM polarization. We measure the TA in the anechoic chamber at Xidian University, China. The distance from TX to TA is 0.21m and from RX to TA 3m. The height of TX to the ground is 1.5 m. The heights of RX and TA to the ground are 3 m. Fig. 13 shows the normalized radiation pattern of the measurements. It can be seen that there is a certain decrease in the main beam gain of other

Fig. 11 Manufactured array antenna with 30 × 30 elements.

Fig. 12 TA under test in microwave chamber at Xidian University.

Fig. 13 Measured normalized radiation patterns of the transmitarray with 30 × 30 DCR elements.

Fig. 14 Comparison between the simulated and measured results of the normalized radiation pattern at 10 GHz.

Fig. 15 The maximum gain versus frequency within the operational frequency band.

Table II Comparison of the proposed transmitarray with referenced transmitarrays

Ref	Numbers of layers	Phase range (°)	Freq. (GHz)	Gain (dB)	1dB Bandwidth
[1]	3	360	9.7	23	5.7%
[2]	2	353	10	21.9	3.9%
[3]	2	305	20	33	5.9%
This work	2	360	10	21.63	25%

frequency points in the main represents the manufactured array. Tx and Rx represent the transmitting horn and the receiving horn, respectively, and during the measurement that the polarizations of RX and TX horn beam direction of the operating frequency band of 10 GHz as the center frequency. The peak gain of the measurement is 21.63dB at a center frequency 10 GHz. It is generally consistent with the simulation. Fig. 14 shows the comparison of the normalized radiation pattern for the center frequency 10 GHz simulation and measurement.

Although there is a deviation in the main beam direction, the overall agreement is good. The processing error and the instability of the plate during the experiment are the main causes of measurement deviation. To demonstrate its gain bandwidth, Fig. 15 shows the relationship of gain as a function of frequency. The 1-dB relative bandwidth of the center operating frequency of 10 GHz is 25%, and the absolute operating bandwidth is from 8.4 GHz to 10.8 GHz. Table II is the comparison of the proposed TA with referenced TAs.

5. Conclusion

This work gives the and design ideas and process of a 1-bit digital coding broadband transmitarray based on a notched square ring structure. To realize the coding antenna, two kinds of unit cells with 0 and π transmission phase are used to mimic “0” and “1” codes for 1-bit digital coding sequences by fuzzy phase control theory. This coding broadband transmitarray was designed, manufactured and measured. The measured results show that the transmitarray element proposed in this paper has 1-dB bandwidth reaches 25% (8.4GHz-10.8GHz). The aperture efficiency at a center frequency of 10GHz is 24%.

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References

- [1] C.G.M. Ryan, *et al.*: “A wideband transmitarray using dual-resonant double square rings,” *IEEE Trans. Antennas Propag.* **58** (2010) 1486 (DOI: [10.1109/TAP.2010.2044356](https://doi.org/10.1109/TAP.2010.2044356)).
- [2] B. Rahmati and H.R. Hassani: “Low-profile slot transmitarray antenna,” *IEEE Trans. Antennas Propag.* **63** (2015) 174 (DOI: [10.1109/TAP.2014.2368576](https://doi.org/10.1109/TAP.2014.2368576)).
- [3] C. Tian, *et al.*: “Circularly polarized transmitarray antenna using low-profile dual-linearly polarized elements,” *IEEE Antennas Wireless Propag. Lett.* **16** (2017) 465 (DOI: [10.1109/LAWP.2016.2583486](https://doi.org/10.1109/LAWP.2016.2583486)).
- [4] J. Yu, *et al.*: “Design of a transmitarray using split diagonal cross elements with limited phase range,” *IEEE Antennas Wireless Propag. Lett.* **15** (2016) 1514 (DOI: [10.1109/LAWP.2016.2517019](https://doi.org/10.1109/LAWP.2016.2517019)).
- [5] A.H. Abdelrahman, *et al.*: “High-gain and broadband transmitarray antenna using triple-layer spiral dipole elements,” *IEEE Antennas Wireless Propag. Lett.* **13** (2014) 1288 (DOI: [10.1109/LAWP.2014.2334663](https://doi.org/10.1109/LAWP.2014.2334663)).
- [6] Q. Luo, *et al.*: “Wideband transmitarray with reduced profile,” *IEEE Antennas Wireless Propag. Lett.* **17** (2018) 450 (DOI: [10.1109/LAWP.2018.2794605](https://doi.org/10.1109/LAWP.2018.2794605)).
- [7] W. An, *et al.*: “A double-layer transmitarray antenna using malta crosses with vias,” *IEEE Trans. Antennas Propag.* **64** (2016) 1120 (DOI: [10.1109/TAP.2015.2513427](https://doi.org/10.1109/TAP.2015.2513427)).
- [8] L. Dussot: in *Aperture Antennas for Millimeter and Sub-millimeter Wave Applications* (Springer International Publishing, Germany, 2017) 191-220.
- [9] X.-J. Yi, *et al.*: “A double-layer highly efficient and wideband transmitarray antenna,” *IEEE Access* **7** (2019) 23285 (DOI: [10.1109/ACCESS.2019.2893608](https://doi.org/10.1109/ACCESS.2019.2893608)).
- [10] Q. Luo, *et al.*: “Wideband transmitarray with reduced profile,” *IEEE Antennas Wireless Propag. Lett.* **17** (2018) 450 (DOI: [10.1109/LAWP.2018.2794605](https://doi.org/10.1109/LAWP.2018.2794605)).
- [11] N. Yu, *et al.*: “Light propagation with phase discontinuities: generalized laws of reflection and refraction,” *Science* **334** (2011) 333 (DOI: [10.1126/science.1210713](https://doi.org/10.1126/science.1210713)).
- [12] C.D. Giovampaola and N. Engheta: “Digital metamaterials,” *Nature Mater.* **13** (2014) 1115 (DOI: <https://doi.org/10.1038/nmat4082>).

- [13] T.J. Cui, *et al.*: “Coding metamaterials, digital metamaterials and programmable metamaterials,” *Science & Applications* **3** (2014) 1 (DOI: <https://xs.scribbr.com/https://doi.org/10.1038/lsa.2014.99>).
- [14] S. Yu, *et al.*: “One-bit digital coding broadband reflectarray based on fuzzy phase control,” *IEEE Antennas Wireless Propag. Lett.* **16** (2017) 1524 (DOI: [10.1109/LAWP.2017.2647743](https://doi.org/10.1109/LAWP.2017.2647743)).
- [15] F. Liu, *et al.*: “Dual-band metasurface-based decoupling method for two closely packed dual-band antennas,” *IEEE Trans. Antennas Propag.* **68** (2019) 552 (DOI: [10.1109/TAP.2019.2940316](https://doi.org/10.1109/TAP.2019.2940316)).
- [16] J. Guo, *et al.*: “Meta-surface antenna array decoupling designs for two linear polarized antennas coupled in H-plane and E-plane,” *IEEE Access* **7** (2019) 100442 (DOI: [10.1109/ACCESS.2019.2930687](https://doi.org/10.1109/ACCESS.2019.2930687)).
- [17] S. Luo, *et al.*: “A low mutual coupling antenna array with gain enhancement using metamaterial loading and neutralization line structure,” *Applied Computational Electromagnetics Society Journal* **34** (2019) 411.
- [18] Y. Kai, *et al.*: “Mutual coupling reduction of a MIMO antenna array using 3-D novel meta-material structures,” *Applied Computational Electromagnetics Society Journal* **33** (2018) 758.
- [19] J. Tao, *et al.*: “A low mutual coupling MIMO antenna using periodic multi-layered electromagnetic band gap structures,” *Applied Computational Electromagnetics Society Journal* **33** (2018) 305.
- [20] K.-W. Lam, *et al.*: “Implementation of transmitarray antenna concept by using aperture-coupled microstrip patches,” *Asia-Pacific Microwave Conference* (1997) 433 (DOI: [10.1109/APMC.1997.659416](https://doi.org/10.1109/APMC.1997.659416)).
- [21] H. Sun and W. Zhang: “Design of broadband element of transmitarray with polarization transform,” *Int. Workshop on Antenna Technology: Small and Smart Antennas, Metamaterials and Applications* (2007) 287 (DOI: [10.1109/IWAT.2007.370131](https://doi.org/10.1109/IWAT.2007.370131)).
- [22] L. Chang, *et al.*: “A three-layer transmitarray element with 360° phase range,” *IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting* (2015) 1868 (DOI: [10.1109/APS.2015.7305323](https://doi.org/10.1109/APS.2015.7305323)).
- [23] Y. Cai, *et al.*: “A novel ultrawideband transmitarray design using tightly coupled dipole elements,” *IEEE Trans. Antennas Propag.* **67** (2019) 242 (DOI: [10.1109/TAP.2018.2878079](https://doi.org/10.1109/TAP.2018.2878079)).
- [24] W. Pan, *et al.*: “An amplifying tunable transmitarray element,” *IEEE Antennas Wireless Propag. Lett.* **13** (2014) 702 (DOI: [10.1109/LAWP.2014.2313596](https://doi.org/10.1109/LAWP.2014.2313596)).
- [25] G. Liu: “High efficiency transmitarray antenna research,” *University of Chinese Academy of Sciences* (2016) 64.
- [26] S.H.R. Tuloti, *et al.*: “High-efficient wideband transmitarray antenna,” *IEEE Antennas Wireless Propag. Lett.* **17** (2018) 817 (DOI: [10.1109/LAWP.2018.2817363](https://doi.org/10.1109/LAWP.2018.2817363)).
- [27] R.H. Phillion and M. Okoniewski: “Lenses for circular polarization using planar arrays of rotated passive element,” *IEEE Trans. Antennas Propag.* **59** (2011) 1217 (DOI: [10.1109/TAP.2011.2109694](https://doi.org/10.1109/TAP.2011.2109694)).
- [28] M. Euler and V.F. Fusco: “Frequency selective surface using nested split ring slot elements as a lens with mechanically reconfigurable beam steering capability,” *IEEE Trans. Antennas Propag.* **58** (2010) 3417 (DOI: [10.1109/TAP.2010.2055814](https://doi.org/10.1109/TAP.2010.2055814)).
- [29] Y. Li and L. Li: “Broadband microstrip beam deflector based on dual-resonance conformal loops array,” *IEEE Trans. Antennas Propag.* **62** (2014) 3028 (DOI: [10.1109/TAP.2014.2314741](https://doi.org/10.1109/TAP.2014.2314741)).
- [30] Remski: “Analysis of PBG surfaces using Ansoft HFSS,” *Mi-crow. J.* **43** (2000) 190.