1-Bit Phase Resolution Wideband Multi-Polarized Transmitarray for Ku-Band Application

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Abstract- This paper proposes a novel 1-bit transmitarray for Ku-band applications, featuring wide bandwidth, compatibility with multiple polarizations, and simple structure. The design incorporates two units with a 180° transmission phase difference, realized using slotted circular patches. Due to the rotational symmetry of the circular patch, these units can receive and transmit electromagnetic waves with different polarizations without mechanical rotation. Both unit cells achieve a transmission coefficient higher than − 1-dB within the frequency range of 11.7 - 20.5 GHz. Leveraging these high-performance unit cells, the transmitarray achieves a wide 3-dB gain bandwidth of 42.07%, a peak realized gain of 24.48 dBi/dBic, and a peak aperture efficiency of 28.4%. This advanced design significantly enhances the efficiency and effectiveness of satellite communication systems and other applications that require high-gain, wideband, and polarization-independent transmitarrays.

I. Introduction

The increasing demands of beyond 5G (B5G) and 6G wireless communication systems have driven the development of high-performance antennas [1]. These advanced systems require antennas that deliver superior signal strength, enhanced data throughput, and improved energy efficiency to meet strict performance criteria. Thus, high-gain antennas have become crucial to support these modern wireless networks' rising data rates and energy efficiency requirements.

To address these challenges, transmitarrays (TA) have emerged as a flexible and efficient solution. They offer numerous benefits, including high gain [2], wide bandwidth [3],[4], lightweight [5], and polarization flexibility [6], making them particularly suitable for a range of communication applications such as satellite, radar, and wireless systems. The ability of TA to meet the high-performance requirements of contemporary communication systems positions them as a vital technology in the ongoing evolution of wireless communications.

This paper proposes a novel TA that achieves wideband performance, lightweight design, high gain, and polarization flexibility simultaneously. The TA is fed by a cone horn, which allows easy polarization changes by adjusting the amplitude and phase of the two input ports, enabling transitions between horizontal polarization, vertical polarization, left-hand circular polarization, and right-hand circular polarization. The performance of the TA under different incident waves will be illustrated in detail.

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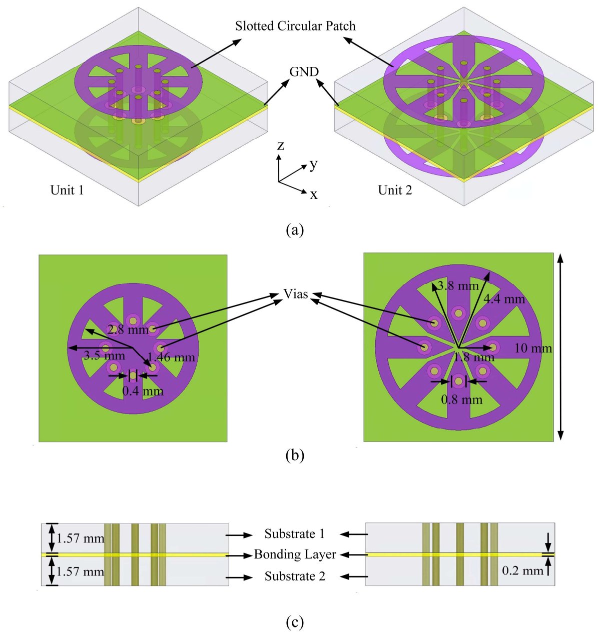

Figure 1. Configurations of the unit cells. (a) 3D view, (b) top view, and (c) side view.

II. TA Design

A. 1-Bit Unit Cells

Fig.1 illustrates the configurations of the units with a 180° transmission phase difference. As shown in Fig. 1(a), each unit comprises three metal layers: the top and bottom layers serve as the receiving and transmitting layers, respectively, while the middle layer acts as the ground. The top and bottom metal layers are interconnected by eight vias, which are isolated from the ground by eight circular windows. Detailed dimensions of the units are provided in Fig. 1(b) and (c).

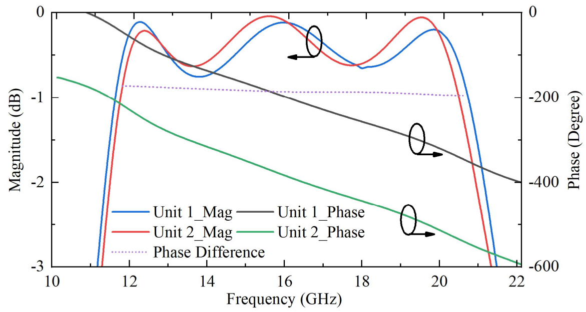

Figure 2. Simulated transmission coefficients and phase difference of the units.

As depicted in Fig. 1(c), the units consist of two identical substrate layers and a bonding layer. Both substrate layers, designated as Substrate 1 and Substrate 2, have a relative permittivity of 2.2 and a dielectric loss tangent of 0.0009. The bonding layer has a relative permittivity of 3.52 and a dielectric loss tangent of 0.0041.

Fig. 2 presents the simulated magnitude and phase of the transmission coefficients for the two units. It is evident that these units maintain a high transmission coefficient of approximately -1 dB across a broad overlapping frequency range of 11.7 - 20.5 GHz. Additionally, the transmission phase difference between the two units remains remarkably stable within this frequency range, consistently around 180°.

B. *Configuration of the TA*

Fig. 3 illustrates the configuration and phase distribution of the proposed TA. The TA has an aperture size of 160 mm × 160 mm and consists of 16 × 16 elements. The focal length-to-diameter ratio (f/D) is set to 1.

To achieve high gain, it is essential that the electromagnetic waves passing through the TA surface remain in-phase. Therefore, the elements on the TA surface must be well-designed to compensate for any phase differences in the signals received by the receiving layer. Assuming the position of the *i*th element is (x_i, y_i), the compensation phase for this element can be calculated using the following equation:

$$k \times (r_{mn} - r_0) + \varphi_{mn} = 2n\pi, n = 0, \pm 1, \ldots, \qquad (1)$$

where k is the wavenumber in free space, r_{mn} is the distance between the phase center of the horn and the *i*th element. r_0 is the distance between the phase center of the horn and the center of the TA. The selection of units is according to the following rule:

$$Unit\ 1\ if\ \ 90° \leq \varphi_{mn} < 270° \qquad (2.a)$$

$$Unit\ 2\ if\ \ \varphi_{mn} < 90°\ or\ \varphi_{mn} \geq 270° \qquad (2.b)$$

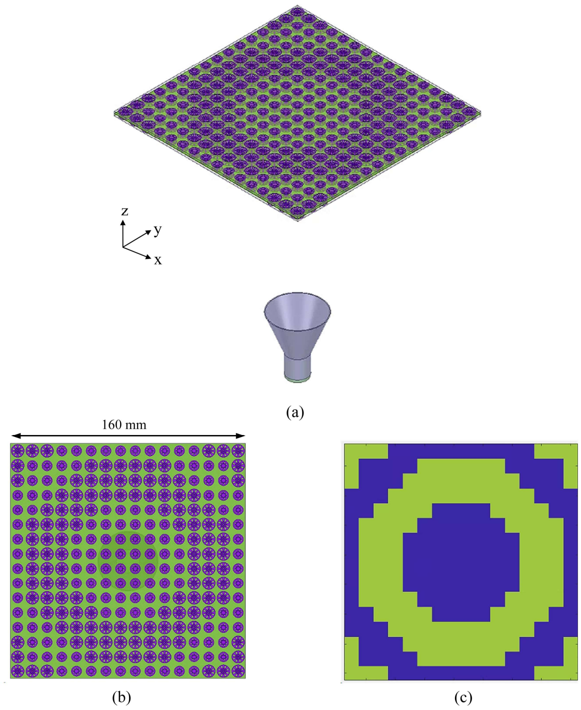

Figure 3. The (a) 3D view, (b) top view and (c) phase distribution of the proposed TA.

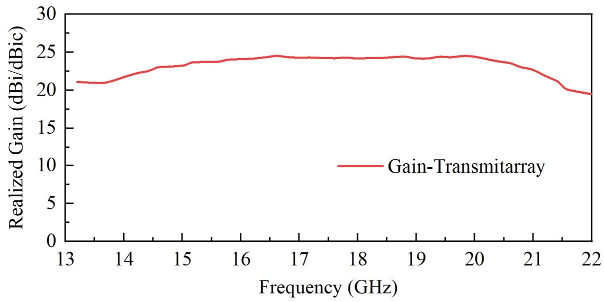

Figure 4. Realized gains of the proposed TA.

C. *Performance of the TA*

Due to the inherent symmetry of the unit cells, only the results for the horizontal (E-plane is yoz-plane) and right-hand circular polarizations are given here. As can be seen in Fig. 4, The TA shows a peak realized gain of 24.48 dBi/dBic when illuminated by a linearly polarized/circularly polarized horn. The 3-dB gain bandwidth is 42.07% (13.91- 21.32 GHz).

The aperture efficiencies in this paper are calculated by using:

$$\eta = \frac{G}{G_{ideal}}, \qquad (3)$$

$$G_{ideal} = \frac{4\pi A}{\lambda^2}, \qquad (4)$$

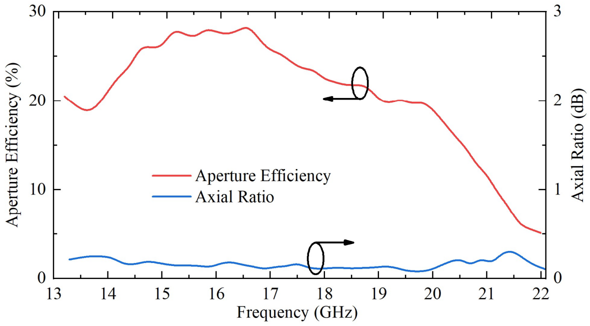

Figure 5. Aperture efficiency and axial ratio (AR) of the proposed TA.

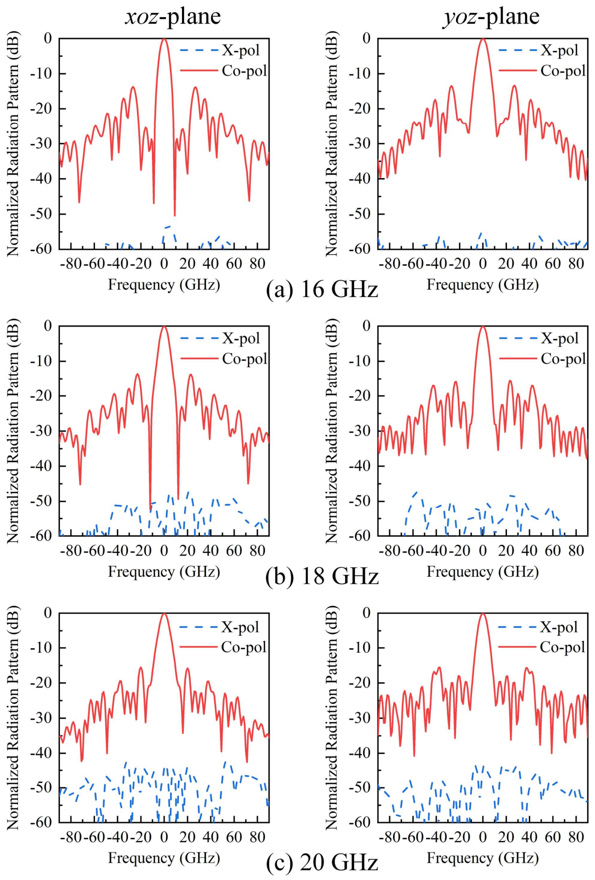

Figure 6. Normalized radiation patterns of the proposed TA illuminated by linearly polarized horn at (a) 16 GHz, (b) 18 GHz, and (c) 20 GHz.

where η is the aperture efficiency, G is the realized gain of the TA, G_{ideal} is the ideal gain, A is the aperture size of the TA. As can be observed in Fig. 5, the peak aperture efficiencies of the proposed TA is 28.4% when illuminated by the linearly polarized and right-hand circularly polarized horns. The axial ratios are below 0.3 dB within the working frequency range.

The radiation patterns of the proposed TA, illuminated by linearly polarized and circularly polarized horns, are shown in

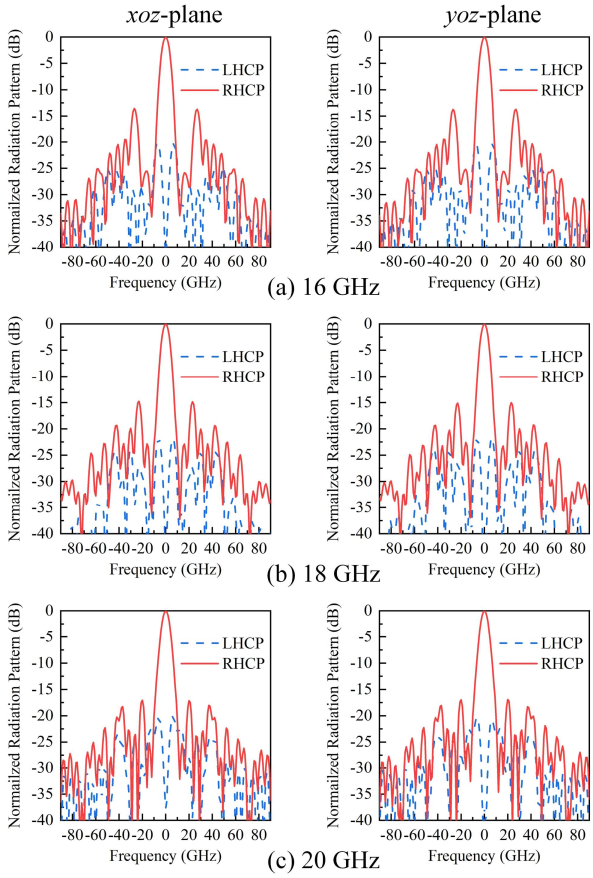

Figure 7. Normalized radiation patterns of the proposed TA illuminated by circularly polarized horn at (a) 16 GHz, (b) 18 GHz, and (c) 20 GHz.

TABLE I
COMPARISON OF THE PREVIOUSLY PRESENTED 1-BIT TA

Ref.	3-dB GBW	f_0 (GHz)	Peak AE	Size ($\lambda_0 \times \lambda_0$)	Profile (λ_0)
[1]	16.5%	8	30.4%	7.56×5.25	0.08
[7]	15.2%	8.4	28.5%	8.17×5.7	0.085
[8]	~4.3%	5.8	22.4%	5.85×5.85	0.077
Pro.	**42.07%**	**17.62**	**28.4%**	**9.40×9.40**	**0.196**

GBW means gain bandwidth, AE is the aperture efficiency. *The results of this work are based on simulation.

Fig. 6 and 7, respectively. It can be observed that the cross-polarization levels are below -43 dB and -25.7 dB in these two cases.

Table I compares the proposed 1-bit TA with previously reported designs, highlighting its superior performance. The proposed 1-bit TA achieves a 3-dB gain bandwidth of 42.07%, which is significantly higher than the 16.5% [1], 15.2% [7], and 4.3% [8] reported for other designs. With a peak aperture efficiency of 28.4%, it is comparable to the 30.4% and 28.5% reported in references [1] and [7], respectively, and superior to the 22.4% reported in reference [8].

In summary, the proposed 1-bit TA excels in gain bandwidth while maintaining acceptable aperture efficiency, making it an excellent candidate for advanced satellite and radar communications.

III. CONCLUSION

In this paper, we introduce a 1-bit transmitarray designed for Ku-band applications. The unit cells employed in this design exhibit broad 1-dB transmission bandwidths and maintain a highly stable transmission phase difference of approximately 180°. The proposed transmitarray supports various polarizations, including linear and circular polarizations, and features an extensive 3-dB gain bandwidth. The sidelobe level (SLL) of this design is approximately 13 dB, attributed to the low phase resolution. It can be improved by enhancing the phase resolution. All the advantages of this design make it an excellent candidate for future applications in satellite communications, radar systems, and wireless communication networks.

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