

Special Topic: Millimeter-Wave and Terahertz Phased-Array and System-Integration Technologies

One-dimensional planar multi-beam dual-polarized transmitarray for large-scale hybrid beamforming system

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Low-complexity large-scale digital-analog hybrid beamforming systems have emerged as a promising solution for real-time imaging, multi-target detection, and high-capacity wireless communication [1]. In such systems, digital beamforming is typically performed in one dimension, while analog beamforming generating predefined multi-beam patterns is applied in the orthogonal dimension, as illustrated in Figure 1(a). Traditional one-dimensional (1-D) multi-beam analog beamforming subarrays adopt methods such as Butler matrices, Nolen matrices, Rotman lenses, and Luneburg lenses. However, their complex feed networks, insertion loss, bulky structure, and large profile limit their application in large-scale hybrid beamforming systems. In contrast, as a favorable alternative, spatially fed 1-D multi-beam transmitarrays have gained extensive attention [2, 3].

Nowadays, due to the growing demands of modern wireless applications, the need for wide coverage, enhanced beamforming capabilities, and high system capacity is becoming urgent. These stringent requirements highlight the necessity for the 1-D planar multi-beam dual-polarized transmitarrays with stable multi-beam gain, high scalability without producing grating lobes, and dual polarizations [4].

To tackle the challenge, this work proposes a 1-D planar multi-beam dual-polarized transmitarray. First, the sliding aperture technique theory is improved mathematically by developing a novel criterion for selecting optimal parameters. The design process of the sliding aperture technique is simplified without complex iteration. Moreover, based on the sliding aperture theory, the 1-D planar multi-beam dual-polarized transmitarray is constructed, which features scalability to 2-D large-scale digital-analog hybrid beamforming systems without grating lobes in two dimensions. The proposed 1-D planar multi-beam dual-polarized transmitarray generates five pairs of dual-polarized beams, covering a scanning range of $\pm 30^\circ$ with stable gain.

Analysis and design. As depicted in Figures 1(b) and (c), consider the design of a 1-D multi-beam transmitarray as an example to illustrate the sliding aperture technique. The maximum and the minimum beam angles of the transmitarray are θ and $-\theta$. The beams are symmetrically distributed with respect to the y -axis. The 1-D feed array is positioned at $y = 0$, and the corresponding 1-D unit array is located at $y = l_0$, where l_0 represents the distance between the feed array and the unit array. Multi-beam is

independently excited by its corresponding feed. The illuminated transmitarray units convert the cylindrical waves from feeds into planar waves, steering the beams toward the intended directions.

Assuming a feed located at O_1 , the illuminated aperture of the transmitarray lies in $x \in [0, 2x_0]$ (aperture 1), where x denotes the coordinate of the transmitarray units and x_0 is the distance from O_1 to the origin. The aperture 1 covers half of the overall aperture L , generating beam 1, which is collimated toward the maximum steering angle θ . The compensation phase ϕ_1 of aperture 1 can be obtained as

$$\phi_1(x) = k_0 \sin \theta x + k_0 \sqrt{l_0^2 + (x - x_0)^2}, \quad x \in [0, 2x_0]. \quad (1)$$

Symmetrically, the feed at O_2 illuminates aperture 2 over $x \in [-2x_0, 0]$, generating beam 2 directed at the angle of $-\theta$. According to the aforementioned calculation, feeds O_1 and O_2 are located at the focal points of apertures 1 and 2.

Considering that the feed is located at O_0 , the central region of the transmitarray (aperture 3) is illuminated, exciting beam 3 along the boresight direction. The aperture 3 spans $x \in [-x_0, x_0]$, covering half of the aperture width L .

Similarly, the ideal compensation phase of aperture 3 is

$$\phi_3(x) = k_0 \sqrt{l_0^2 + x^2}, \quad x \in [-x_0, x_0]. \quad (2)$$

As written in (1), the transmission phase distribution is designed based on the maximum beam angle θ , which deviates from the ideal compensation phase required for boresight radiation, as expressed in (2). This discrepancy leads to phase deviation across aperture 3 when beam 3 is excited. Consequently, the feed O_0 may not coincide with the focal point of aperture 3. The phase deviation on aperture 3 is

$$\Delta\phi_1(x) = \phi_3(x) - \phi_1(x) = k_0 \left(\sqrt{l_0^2 + x^2} - \sqrt{l_0^2 + (x - x_0)^2} - \sin \theta x \right), \quad x \in [0, x_0]. \quad (3)$$

Owing to the symmetry of the configuration, the phase deviation $\Delta\phi_1$ is analyzed to simplify the evaluation.

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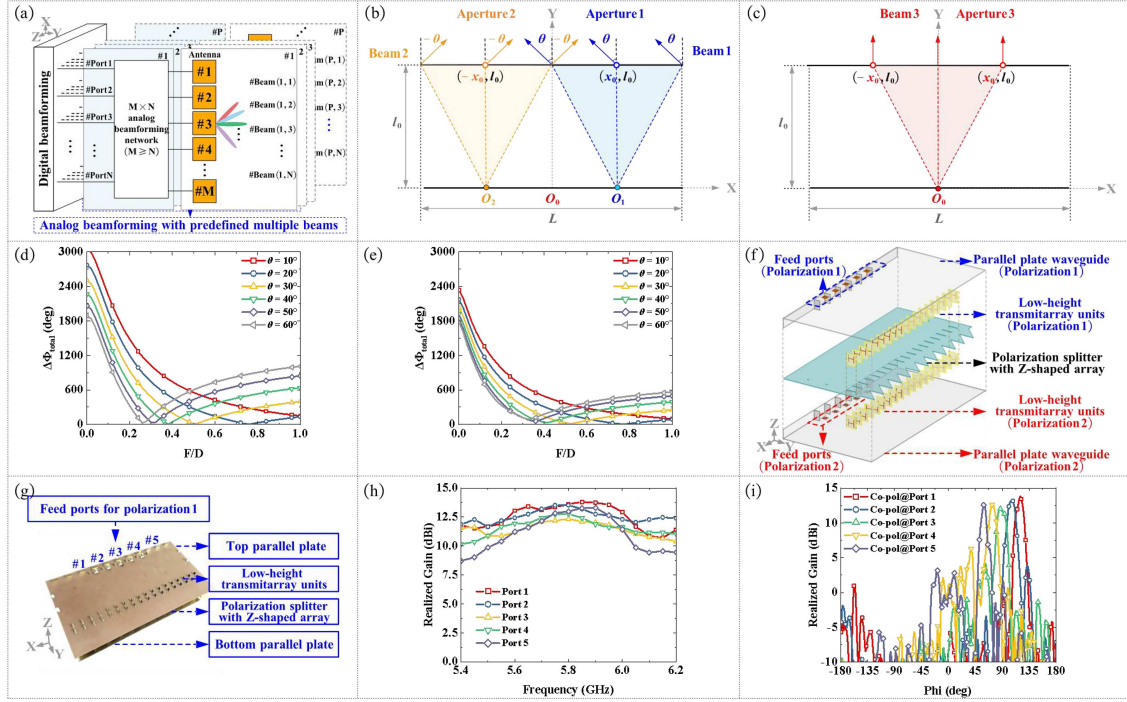


Figure 1 (Color online) One-dimension planar multi-beam dual-polarized transmitarray for large-scale hybrid beamforming system. (a) Configuration of the 2-D large-scale digital-analog hybrid beamforming array; (b) the sliding aperture technique (apertures 1 and 2 illuminated by feed O_1 and O_2); (c) the sliding aperture technique (aperture 3 illuminated by feed O_0); (d) the total phase deviation versus F/D for different maximum beam angles (feed at O_0); (e) the total phase deviation versus F/D for different maximum beam angles (feed at $x = L/8$); (f) configuration of the proposed 1-D planar multi-beam dual-polarized transmitarray; (g) photograph; (h) measured gain versus frequency; (i) measured radiation pattern.

To further simplify (3), the Taylor expansion is applied to (1) at $x = x_0$ and (2) at $x = 0$ up to the third order. The normalized phase deviation across aperture 3 is

$$\Delta\Phi(x) = k_0(x_0/l_0 - \sin\theta)x, \quad x \in [0, x_0]. \quad (4)$$

The derivative of phase deviation can also be calculated to provide insight into the beam distortion. When $x_0 = L/4$, and $F/D = l_0/L$, to minimize the phase deviation across the aperture, the F/D and the maximum beam angle θ satisfy

$$\Delta\Phi(x)' = k_0(1/(4 \times F/D) - \sin\theta) = 0; \quad F/D = 1/(4 \sin\theta). \quad (5)$$

With the requirements in (5), the phase deviation and its derivative are zero. There is no phase error on aperture 3, and the feed O_0 lies at the focal point of aperture 3 as well.

Consequently, the optimal F/D can be formulated mathematically, which is a pivotal criterion to minimize phase deviation of transmitarrays in the sliding aperture technique. For different maximum beam angles and F/D , the total phase deviation $\Delta\Phi_{\text{total}}$ on aperture 3 is calculated, as shown in Figure 1(d). The simulated optimal F/D value shows good agreement with the theoretical prediction given by the closed-form (5). With a similar calculation, the phase deviation of the feed at $x = L/8$ is presented in Figure 1(e).

In conclusion, as the phase error of feed O_0 decreases to the optimal value, the counterpart of feed at $x = L/8$ declines effectively and achieves the minimum. As the maximum beam angle increases, the F/D ratio of transmitarrays designed using the sliding aperture technique decreases, resulting in a more compact structure.

The 1-D planar multi-beam dual-polarized transmitarray. The configuration of the proposed 1-D planar multi-beam dual-polarized transmitarray is shown in Figure 1(f). The overall dimensions of the structure are 380 mm × 190 mm × 35 mm. The proposed transmitarray consists of two identical 1-D multi-beam single-polarized transmitarrays arranged back-to-back with a polarization splitter to enable dual-polarization. A photograph of the fabricated prototype is presented in Figure 1(g), with five ports of polarization 1 located on the top and others of polarization 2 positioned on the bottom. The beams 1–5 are generated with ports 1–5. Five couples of beams are collimated to -30° , -16° , 0° , 16° , and 30° , with a coverage of $\pm 30^\circ$. The measured gain responses across frequency for the five beams are plotted in Figure 1(h). The gain of five beams fluctuates from 12.34 to 13.62 dBi at 5.8 GHz. The measured radiation patterns are presented in Figure 1(i).

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