An Ultra-wideband Reflectarray Antenna Using Connected Dipoles for Multifunctional Systems

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***Abstract*—A novel ultra-wideband reflectarray antenna using connected dipoles for multifunctional systems is proposed in this paper. The reflectarray element is composed of an elliptical dipole and a slot line which are printed on a single substrate. Neighboring elements are connected to achieve the ultra-wide bandwidths for both the impedance and the radiation pattern bandwidths simultaneously. By combining the advantages of conventional reflectarray antennas and connected array antennas, the proposed reflectarray antenna achieves ultra-wide bandwidth with greatly reduced feeding complexity and fabrication cost. As a proof of concept, a 354-element reflectarray antenna is designed. The presented reflectarray antenna maintains undistorted beams and high antenna gain over a bandwidth of 100%, i.e., from 10 to 30 GHz.**

***Index Terms*—connected arrays, reflectarray antenna, ultra-wideband arrays, multifunctional antennas.**

I. INTRODUCTION

Reflectarray antennas have attracted increasing attention in recent decades due to their advantages, such as low profile, light weight, low cost, simplified feed network, as well as high gain [1]. However, despite these advantages, the most significant drawback of reflectarray antennas is the narrow bandwidth [2]. The narrow bandwidth mainly stems from two factors: the inherent narrow-band characteristics of the radiation elements and the differential spatial phase delay [1]. For the small and medium sized reflectarray antennas, the first factor is dominated [2].

In order to overcome the bandwidth limitation of the radiation elements, various methods have been proposed for reflectarrays in recent years, such as employing multi-resonance elements [3], sub-wavelength elements [4], rings with attached phase delay lines [5], and rectangular patches embedded with inverted L-shaped slots [6]. Although the bandwidth of the reflectarrays is significantly improved by using the aforementioned elements, the overall bandwidth of them rarely exceeds one octave. To further improve the bandwidth performance of reflectarrays, tightly coupled dipole element was used, which demonstrated a breakthrough of 3:1 bandwidth for reflectarrays [7]. However, the complicated array structure especially the interleaved substrate arrangement obstructs its application.

In this paper, a novel ultra-wideband reflectarray antenna using connected dipole elements for multifunctional systems is proposed. The concept of connected dipole elements is introduced into the design of the proposed reflectarray antenna, which is inspired by tightly coupled arrays [8] and connected array antennas [9]. In both arrays, the adjacent elements are connected or closely placed to increase the mutual coupling between neighboring elements. Like the designs in [10] and [11], these array antennas have a wide impedance bandwidth. The proposed reflectarray antenna combines the advantages of conventional reflectarray antennas and connected array antennas. Consequently, the proposed reflectarray antenna achieves ultra-wide bandwidth with rather simple array structure.

II. REFLECTARRAY ANTENNA DESIGN AND ANALYSIS

A. Equivalent Distance Delay

In a reflectarray, the required phase delay of a reflectarray element $\Phi(x_i, y_i)$ is given by

$$\Phi(x_i, y_i) = -k_0 \sin\theta_b (x_i \cos\theta_b + y_i \sin\varphi_b) + R_i k_0 \qquad (1)$$

where k_0 is the wave number in free space, and (θ_b, φ_b) is the beam direction of the reflectarray. The position of the element is denoted by (x_i, y_i), and the distance between the element and the phase center of the feed antenna is R_i. In order to eliminate the effects of frequency, (1) is divided by k_0

$$\Phi(x_i, y_i)/k_0 = -\sin\theta_b (x_i \cos\theta_b + y_i \sin\varphi_b) + R_i \qquad (2)$$

Let

$$d(x_i, y_i) = \Phi(x_i, y_i)/k_0 \qquad (3)$$

$$d'(x_i, y_i) = d(x_i, y_i) - d(x_1, y_1) \qquad (4)$$

Then

$$d'(x_i, y_i) = -\sin\theta_b[(x_i - x_1)\cos\theta_b + (y_i - y_1)\sin\varphi_b] + (R_i - R_1) \qquad (5)$$

where $d(x_i, y_i)$ refers to the required equivalent distance delay of the ith reflectarray element, and $d'(x_i, y_i)$ is the renormalized equivalent distance delay. If the value of the calculated renormalized equivalent distance delay $d'(x_i, y_i)$ of the reflectarray element keeps unchanged in a certain band, the reflectarray element can compensate differential spatial phase delay appropriately within such bandwidth [7].

B. Design of the Reflectarray Element

The geometry of the proposed unit cell is shown in Fig. 1. As shown, the reflectarray element consists of an elliptical dipole, a slot line and a ground plane. The elliptical dipole and the slot line are printed on a 0.813 mm Rogers RO4003C substrate with a dielectric constant of 3.55. An air layer is utilized between the substrate and the ground plane to improve the bandwidth performance. The variation of the equivalent distance delay is realized by adjusting the length l of the slot lines. By optimizing the distance dy between adjacent elements and the value of h_2, good reflection coefficient within a wide operation band can be obtained. It is worthy pointing out that the neighboring elements of the proposed reflectarray are directly connected with each other. With this arrangement, the bandwidth of the array can be greatly improved attributed to the strong mutual coupling between elements.

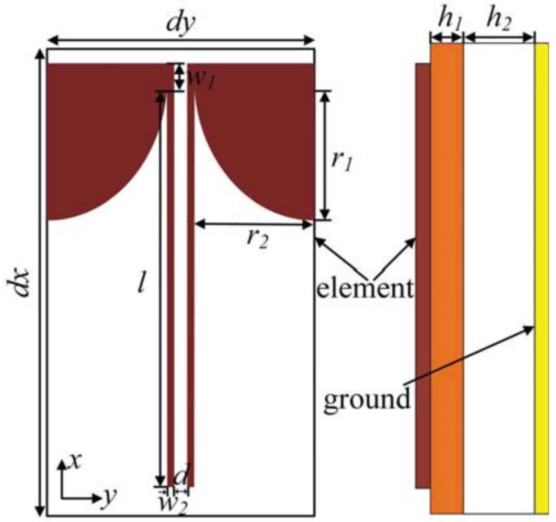


Fig. 1. Geometry of the proposed unit cell design.

Full-wave simulation results of the proposed reflectarray unit cell structure are obtained with the help of ANSYS HFSS. A plane wave polarized along the y-direction with normal incidence is considered. The renormalized equivalent distance delay $d'(x_i, y_i)$ produced by the proposed reflectarray element at different frequencies is illustrated in Fig. 2. Although the renormalized equivalent distance delays of the proposed element for different frequencies are not precisely overlapped, the deviations are small enough, which makes the proposed element satisfy (5) within an ultra-wide frequency range. A function of $d'(l)$ is utilized to design the reflectarray with minimized phase errors, which satisfies the following equation:

$$d'(l) = \sum_{f=f_1}^{f_2} \frac{d_f(l)}{N} \tag{6}$$

where N is the number of frequency points from f_1 to f_2. The curve of calculated $d'(l)$ is also shown in Fig. 2, which is used to calculate the length l of delay line for each reflectarray element.

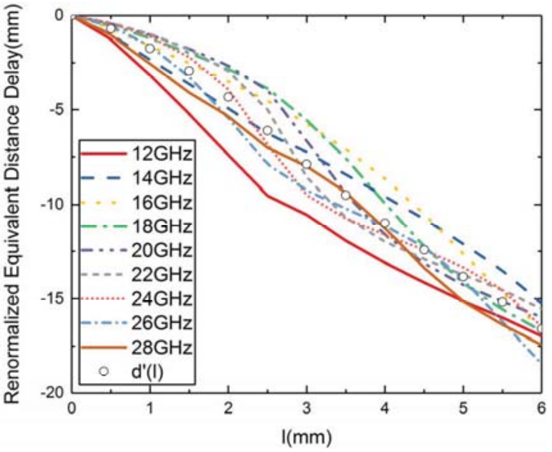


Fig. 2. Calculated renormalized equivalent distance delay of the proposed unit cell.

C. Design of the Feed Antenna

An ultra-wideband double-ridged horn antenna (DRHA) is used as the feed antenna [12]. In the DRHA, ridges are introduced on both broad walls. The configuration of the DHRA is shown in Fig. 3. The simulated $|S_{11}|$ of the feed antenna is shown in Fig. 4. As shown, the feed horn can maintain $|S_{11}|$<-15 dB from 10 GHz to 30 GHz.

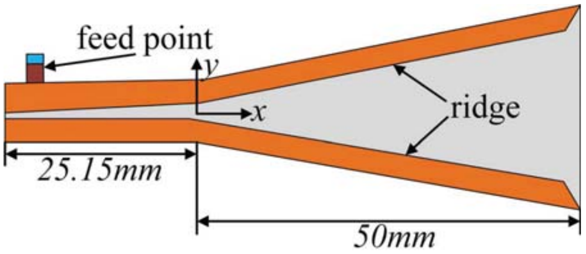


Fig. 3. Configuration of the feed antenna.

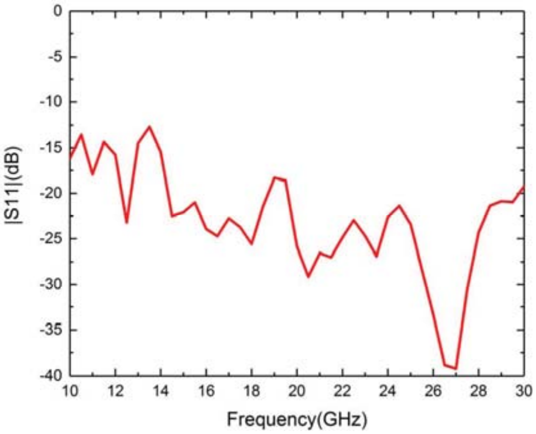


Fig. 4. Simulated |S11| of the feed antenna.

The phase center of the DRHA changes with frequency. Let $p_f(x,y)$ denotes the position of the phase center at frequency *f*. The positions of the phase center at some frequency points are given in Table I. In the reflectarray antenna design, the position of the phase center $p(x,y)$ is calculated by using the following equation:

$$p(x,y)=\sum_{f=f_1}^{f_2}\frac{p_f(x,y)}{N} \tag{7}$$

where N is the number of frequency points from f_1 to f_2.

TABLE I. COORDINATES OF PHASE CENTER (UNIT: mm)

Frequency (GHz)	10	12	14	16
$p_f(x,y)$	(48.3,0)	(48.0,0)	(47.4,0)	(46.1,0)
Frequency (GHz)	18	20	22	24
$p_f(x,y)$	(47.1,0)	(45.7,0)	(43.9,0)	(41.6,0)
Frequency (GHz)	26	28	30	
$p_f(x,y)$	(41.7,0)	(40.9,0)	(39.0,0)	

D. Design of the Reflectarray

The proposed reflectarray antenna is shown in Fig. 5. As shown, the array aperture is octagonal shaped and composed of 354 elements. The focal length F_1 of the reflectarray is chosen to be 91 mm, which equals to a focus/diameter (F/D) ratio of 0.9 to provide a proper illumination while maximize the aperture efficiency. And the distance between the reflectarray and DRHA feed antenna F_2 is 86 mm.

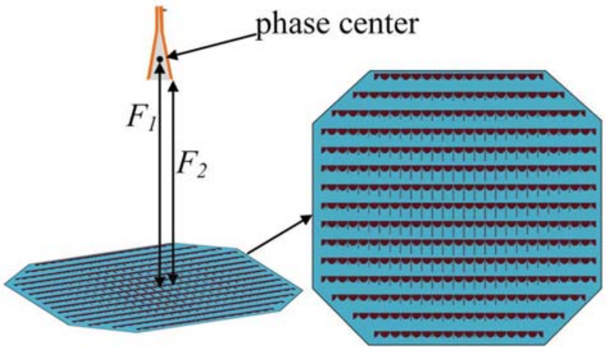
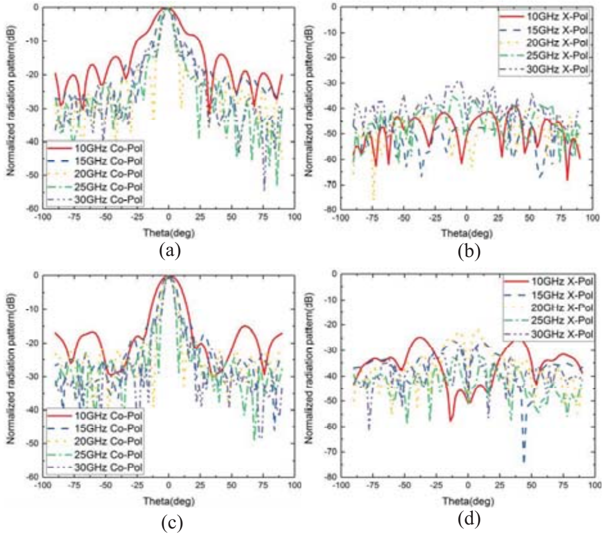


Fig. 5. Configuration of the proposed reflectarray antenna.

III. RESULTS AND DISCUSSION

Fig. 6 presents the simulated normalized patterns of the proposed reflectarray at different frequencies. As can be seen, the radiation patterns are stable within a 3:1 bandwidth. The main beam is not distorted within the frequency range from 10 to 30 GHz. The highest sidelobe level (SLL) in H-plane is about -12.2 dB, and the highest SLL in E-plane is about -8.2 dB. The relative high sidelobe level is mainly due to the spillover effect and the phase error at marginal frequencies. It is also noted that in the main beam region, the simulated cross-pol levels are below -30 and -23 dB in the E- and H-planes, respectively.



(a) (b)

(c) (d)

Fig. 6. Simulated E- and H-plane patterns of the proposed reflectarray at various frequencies. (a) E-plane co-pol patterns. (b) E-plane cross-pol patterns. (c) H-plane co-pol patterns. (d) H-plane cross-pol patterns.

The simulated gain and aperture efficiency of the proposed reflectarray are plotted in Fig. 7. The simulated gain increases monotonically from 15 dB at 10GHz to 25.6 dB at 28.5 GHz. The simulated aperture efficiency (AE) of the antenna is over 23% from 10 to 30 GHz, and the maximum aperture efficiency is 47.5% at the design frequency of 22 GHz.

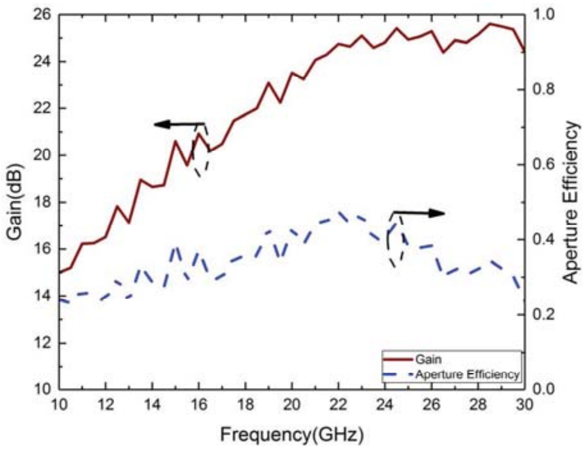


Fig. 7. Simulated gain and aperture efficiency of the proposed reflectarray.

IV. CONCLUSION

This paper presents an ultra-wideband reflectarray design based on connected dipole concept. A simple and novel single-layer element for ultra-wideband reflectarray antenna has been proposed. The connected dipole mechanism is exploited to achieve the ultra-wide bandwidths for both the impedance and the radiation pattern bandwidths simultaneously. Using the connected dipole element, an ultra-wideband reflectarray antenna is designed. The antenna has stable radiation patterns within an ultra-wide operating bandwidth from 10 to 30 GHz. The simulated gain and aperture efficiency within the operating bandwidth are from 15 to 25.6 dB, and from 23% to 47.5%, respectively. The planar array structure and its superior performance make the proposed reflectarray antenna very promising for the multifunctional applications, such as satellite communication and 5G mobile communication.

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