2020 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO) | 978-1-7281-6966-8/20/$31.00 ©2020 IEEE | DOI: 10.1109/NEMO49486.2020.9343589

Recent Development of Tightly Coupled Reflectarray Antenna (TCRA) for Multifunctional Systems

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***Abstract*-The TCRA has been a hot topic in the area of reflectarray design, because it can operate over multi-octave frequency range, enabling it to be deployed in multifunctional systems. This paper presents a detailed review of the recent development of TCRA at the University of Kent and Shenzhen University. To illustrate the evolution of TCRA, three case studies are provided. Firstly, a novel tightly coupled dipole reflectarray antenna whose unit cell is consisted of a tightly coupled dipole and a delay line is introduced. This reflectarray operates from 3.4 to 10.6 GHz with stable radiation patterns. Then, an ultra-wideband reflectarray antenna using connected dipoles is introduced. The reflectarray antenna maintains undistorted beams and high antenna gain from 10 to 30 GHz. In the end, the TCRA employs a polarization converter (PC) to overcome the limitation of bandwidth caused by the ground plane truncation is demonstrated. The antenna has stable radiation patterns and relative high gain within an operating bandwidth from 4 to 20 GHz.**

***Index Terms*—Multifunctional antennas, polarization conversion, reflectarray antenna, tightly coupled arrays, ultra-wideband arrays.**

I. INTRODUCTION

With the development of wireless communication systems, such as satellite communications and 5G mobile communications, ultra-wideband array antennas have received considerable attention because of their potential to realize multiple functions through one single radiating aperture. The diverse functionality of the wireless systems is usually achieved by using various independent antenna arrays operating in different frequency bandwidths. For this reason, the size, weight, cost, and power loss of multifunctional systems can be significantly reduced by using ultra-wideband antennas.

Recently, it has been demonstrated that tightly coupled dipole arrays (TCDAs) can achieve ultra-wideband performance. Generally, there are two ways to design a TCDA, one is the utilization of connected dipoles [1], and the other one is the employment of capacitive coupling elements [2].

On the other hand, reflectarray antennas have attracted increasing attention in recent decades due to their advantages, such as low profile, light weight, low cost, simplified feed network, and high gain [3]. However, despite these advantages, the design of reflectarray antennas is often burdened by the limited bandwidth [4]. In order to break through the bandwidth limitation of reflectarrays, the idea of TCDA was introduced into the design of the reflectarray antenna in [5]. The developed TCRA has demonstrated a breakthrough of 3:1 bandwidth. In [6], a variant-coupling-capacitance method was proposed to improve the aperture efficiency of TCRA at lower frequency. By changing the coupling capacitance between neighboring elements according to their positions in the reflecting surface, the linearity of phase delay line improved at the objective frequency. Aperture efficiency at lower frequency was improved by 21.6%. A dual-polarized reflectarray antenna using tightly coupled element was presented in [7]. The TCRA can work from 1.7GHz to 5GHz without main beam distortion in both polarizations. Although these aforementioned TCRA were effective in improving the bandwidth, the complicated array structure especially the interleaved substrate arrangement obstructs their applications. To keep the fascinating feature of the reflectarray antenna, a novel broadband single-layer TCRA was proposed in [8], which has stable radiation patterns from 12 to 22 GHz.

This paper aims to provide a detailed review of the recent development on TCRA for multifunctional systems. To illustrate the evolution of TCRA, three recent research works demonstrated as three case studies are presented.

II. CASE STUDY 1: AN ULTRA-WIDEBAND TIGHTLY COUPLED DIPOLE REFLECTARRAY ANTENNA

In this case study, a novel ultra-wideband tightly coupled dipole reflectarray antenna is presented. This design combines the advantages of tightly coupled arrays and those of conventional reflectarrays. The proposed TCRA has a wide bandwidth and stable radiation patterns from 3.4 to 10.6 GHz.

A. *TCRA Design*

Fig. 1 shows the configuration of the TCRA element.

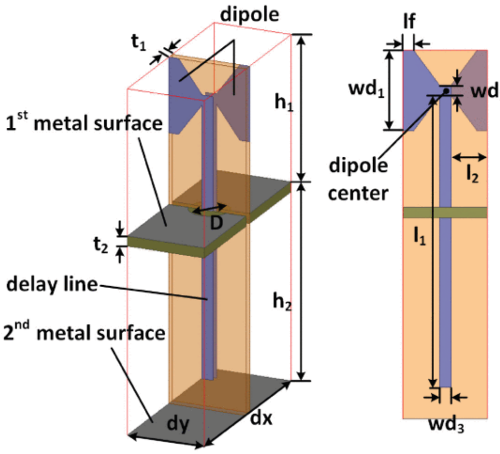


Fig. 1. Configuration of the TCRA element [5].

As shown in Fig.1, the TCRA element consists of a dipole, a delay line, and two metal surfaces. The distance between the top of the element and the first metal surface is h_1, which determines the impedance bandwidth. Once the bandwidth of the TCRA is optimized, the value of h_1 is fixed. The variation of the reflection phase is realized by adjusting the length l_1 of the delay lines. The minimum distance between adjacent elements is 8 mm, which is less than 0.1λ (free space wavelength) at the lowest operating frequency. Since the distance between adjacent elements is quite small, the coupling between the elements is very strong.

The configuration of the TCRA is shown in Fig. 2. A wideband log-periodic dipole array (LPDA) is used as the feed antenna. The array aperture is composed of 26 × 11 elements. The distance between the phase center of the LPDA and reflecting surface is chosen to be 119 mm to provide a proper illumination. And the distance between the top of reflecting surface and LPDA feed antenna is 97.6 mm.

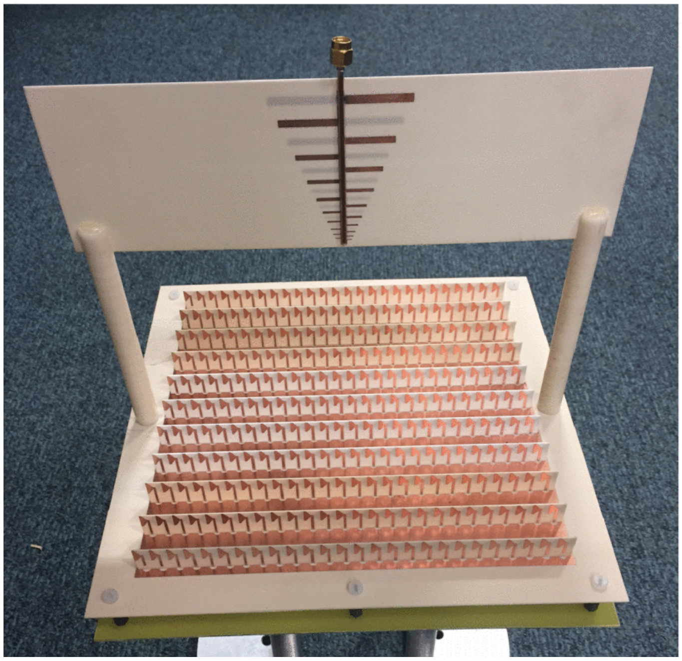


Fig. 2. Configuration of the TCRA [5].

B. *Results and Discussion*

The TCRA has stable radiation patterns within an ultra-wide operating bandwidth from 3.4 to 10.6 GHz. The main beam of the antenna is not distorted or split within the operating bandwidth. The simulated and measured gain and aperture efficiency of the TCRA are plotted in Fig. 3. The simulated gain increases from 12.7 to 21.9 dBi in the working band and peaks at 10 GHz. The measured gain varies from 13.8 to 22.6 dBi and peaks at 10.6 GHz. The simulated aperture efficiency (AE) of the TCRA is over 20% from 3.4 to 10 GHz, and is larger than 17.8% from 10 to 10.6 GHz. The measured AE of the TCRA is over 20% within the operating bandwidth. From these results, it is evident that the strong coupling among array elements helps improve the bandwidth of the reflectarray.

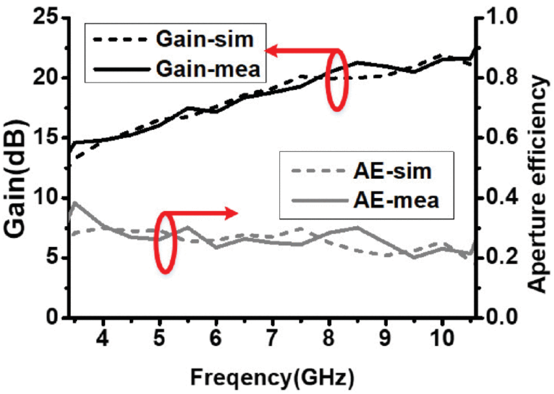


Fig. 3. Simulated and measured gains and aperture efficiency [5].

CASE STUDY 2: A PLANAR ULTRA-WIDEBAND REFLECTARRAY ANTENNA USING CONNECTED DIPOLES

In this case study, a planar ultra-wideband reflectarray antenna using connected dipoles is presented [9]. This antenna combines the advantages of conventional reflectarray antennas and connected array antennas. Neighboring elements are directly connected with each other to improve the array performance. The presented TCRA maintains stable radiation patterns and high antenna gain from 10 to 30 GHz.

A. *Planar TCRA Design*

The geometry of the proposed planar TCRA unit cell is shown in Fig. 4. The TCRA element consists of an elliptical dipole and a slot line connected to the dipole directly. An air layer is applied between the substrate and the ground plane to improve the bandwidth performance. The reflection phase compensation of the TCRA unit cell is realized by adjusting the length l of the slot lines. Ultrawide bandwidth of the unit cell can be obtained by optimizing the distance dy between adjacent elements and the value of h_2. It is worthy pointing out that the neighboring elements of the proposed TCRA are directly connected with each other. In this manner, the coupling between adjacent elements is strong enough to yield a wide impedance bandwidth.

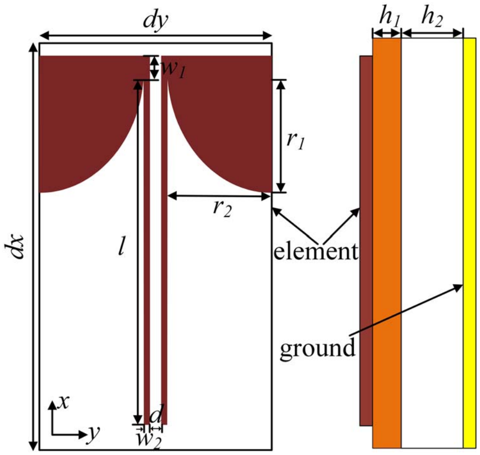


Fig. 4. Geometry of the proposed TCRA unit cell [9].

As shown in Fig. 5, the proposed reflectarray is designed with 503 elements. An ultra-wideband double-ridged horn antenna (DRHA) is used as the feed antenna. To maximize the aperture efficiency, the focal length of the reflectarray is chosen to be 119 mm.

Fig. 5. Configuration of the proposed TCRA.

B. *Results and Discussion*

The simulated and measured gain and aperture efficiency of the proposed TCRA are plotted in Fig. 6. As shown, the simulated gain increases from 15.65 to 27.12 dBi, while the measured gain varies from 14.11 to 27.51 dBi within the operating bandwidth. The measured average aperture efficiency (AE) of the TCRA is about 30% from 10 to 30 GHz, and the measured maximum aperture efficiency is 43.8% at the design frequency of 26 GHz.

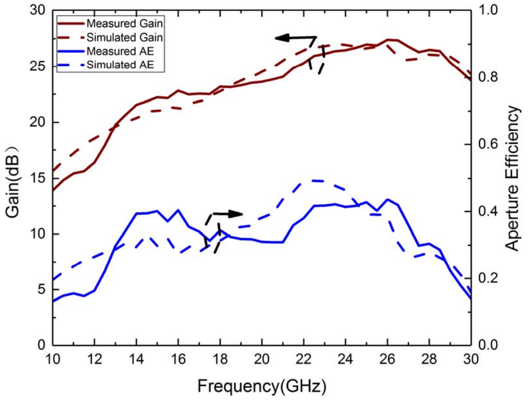


Fig. 6. Simulated and measured gain and aperture efficiency of the proposed TCRA.

CASE STUDY 3: A NOVEL POLARIZATION CONVERTER BASED TCRA

In this case study, a novel polarization converter (PC) based TCRA is proposed. The proposed TCRA employs a polarization converter to overcome the bandwidth limitation of a conventional TCRA. The proposed TCRA has stable radiation patterns from 4 to 20 GHz. Over 5:1 frequency range, the main beam of the reflectarray is not distorted or split and the AE keeps at a reasonable range.

A. *PC Based TCRA Design*

The geometry of the proposed PC based TCRA element is shown in Fig. 7. As shown, the dipole and the slot line are printed on the top layer of the substrate and the PC is printed on the opposite side of the substrate. The PC is introduced to overcome the limitation of bandwidth caused by the ground plane truncation. An air layer with height h is utilized between the substrate and the ground plane to improve the bandwidth performance. The variation of the reflection phase is realized by adjusting the length of the slot lines. The coupling is introduced between the adjacent dipoles. By optimizing the distance p between adjacent elements and the value of h, good reflection coefficient within a wide operation band can be obtained.

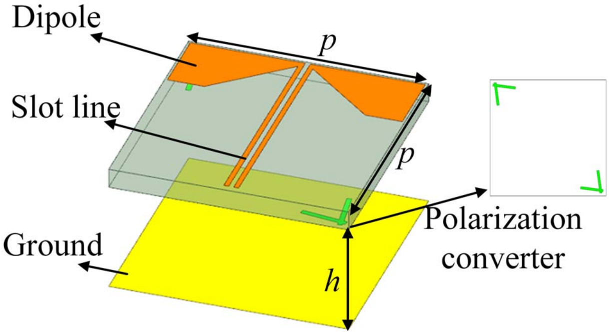


Fig. 7. Geometry of the proposed TCRA element.

The configuration of the proposed TCRA is shown in Fig. 8. An ultra-wideband double-ridged horn antenna (DRHA) is chosen as the feed antenna. The proposed TCRA consists of 177 elements. The distance between the phase center of the DRHA and reflecting surface F is 85 mm to provide a proper illumination with maximum aperture efficiency.

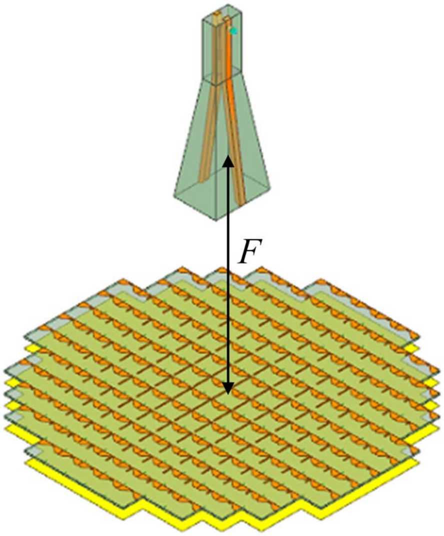
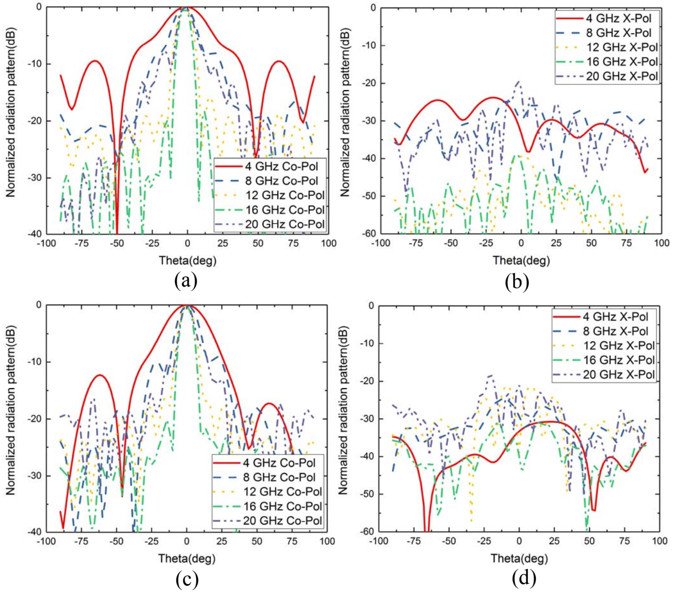


Fig. 8. The configuration of the proposed TCRA.

B. *Results and Discussion*

Fig. 9 shows the simulated normalized radiation patterns of the proposed TCRA at various frequencies. As can be seen, the radiation pattern keeps stable within a 5:1 bandwidth. The shape of the main beam is not distorted within the frequency range from 4 to 20 GHz. The highest sidelobe level (SLL) in H-plane is about -10 dB, and the highest SLL in E-plane is about -8 dB. The relatively 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 -20 dB in both principal planes.



(a) (b)

(c) (d)

Fig. 9. Simulated E- and H-plane patterns of the proposed TCRA 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 TCRA are plotted in Fig. 10. The simulated gain varies from 9 to 24 dBi in the operational band and peaks at 18 GHz. The simulated aperture efficiency (AE) of the TCRA is over 20% from 4 to 19 GHz, and the maximum aperture efficiency is 43.8% at the design frequency of 15 GHz.

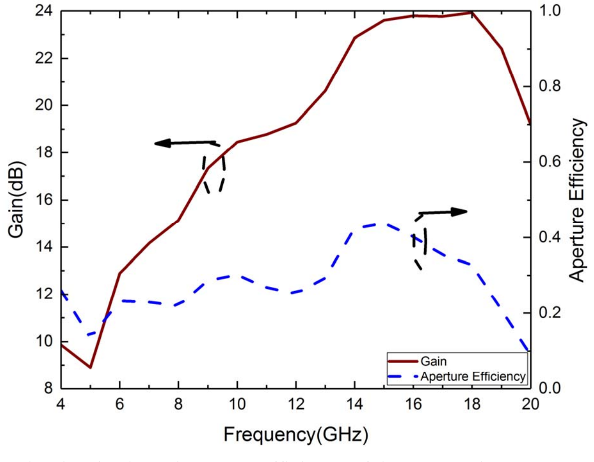


Fig. 10. Simulated gain and aperture efficiency of the proposed TCRA.

III. CONCLUSION

In this paper, a detailed review of recent development of the TCRA is conducted. Three recent research works are presented to demonstrate the evolution of TCRA design. From all presented studies, it is evident that the TCRA indeed breaks through the bandwidth limitation of conventional reflectarrays. Moreover, further performance improvement is also feasible when the TCRA is combined with other techniques such as the polarization converter and metasurfaces.

ACKNOWLEDGMENT

This work is supported in part by the National Natural Science Foundation of China under Grants 61801299 and 62071306, in part by the Natural Science Foundation of Guangdong Province under Grant No. 2020A1515011037, in part by the Shenzhen Science and Technology Program under Grants JCYJ 20170302150411789, JCYJ 20170302142515949, GCZX2017040715180580, GJHZ 20180418190529516.

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