Near-Field Phase Transforming Structures for High-Performance Antenna Systems

Foez Ahmed(1), Muhammad U. Afzal(1), Touseef Hayat(2), Dush Thalakotuna(1), and Karu P. Esselle(1)

(1) School of Electrical and Data Engineering, University of Technology Sydney, NSW, Australia.
(2) School of Engineering, Macquarie University, Sydney, NSW, Australia.

***Abstract*—A review of the state-of-the-art near-field transforming structures (NFTSs) for realizing high-performance antenna systems is presented. The NFTSs are primarily synthesized for near electric field phase transformation for various applications. They can operate from microwave to millimeter-wave bands. This study mainly examines the NFTSs reported for achieving high gain and passive beam-steering antennas with prototyping flexibility for low-profile and low-cost solutions. Furthermore, the optimal fabrication processes for various design concepts are discussed, highlighting a few of them.**

I. INTRODUCTION

Highly directive high-gain and beam-steering antennas are crucial for future generation communication systems, including satellite connectivity through communication-on-the-move platforms [1]. Various technologies have been adopted to achieve high-gain and steering beams of antennas in the literature. Large-scale reflectors, arrays, and lenses are the classical approaches traditionally used for high-gain applications. In contrast, mechanically fully rotatable reflectors, active electronically phased arrays, and reflect/transmit arrays are the conventional way to steer the antenna beams. Despite some merits, these antenna systems have physical and electrical constraints, limiting their deployments in many potential applications. Some are bulky and heavy and require large 3D or lateral space to implement the antenna beam-steering functionalities. Due to active components and feed networks, arrays are lossy. Some techniques are only feasible for the high-end user due to high production costs.

Near-field transforming structures (NFTSs) are a type of additive with a fixed-beam antenna that has sparked much interest over the years due to their potential electromagnetic (EM) wave manipulation capabilities in the near field region of the antenna. To achieve the desired antenna performance, the amplitude, phase, and polarization of the incident EM waves can be translated individually or in combination through the NFTSs. This technique offers many advantages over the traditional high-gain and beam-steering approaches. This paper presents three broad classes of NFTSs developed for high-gain and beam-steering antenna systems using different design and fabrication technologies. It showcases the most recent development of NFTSs reported by our research group in this research domain.

II. ALL-DIELECTRIC NFTSS

Due to its planar configuration, simple feeding technique, and highly directive EM properties, the electromagnetic bandgap resonator antennas (ERAs) were considered alternatives to high-gain antennas. In 2015, however, it was revealed that conventional ERAs suffer from non-uniform aperture phase distribution [2], resulting in degraded EM performance. The near-field phase transforming structure of its first kind was proposed to resolve the phase errors by integrating several non-planar dielectric rings (Rexolite 1422) with fixed permittivity [2]. Each ring with different heights introduces the required phase delay to the incident EM waves, resulting in a uniform phase at the output plane; hence, significantly improving the antenna performance. The directivity was improved by 9 dB (from 12.3 to 21.6 dBi) with peak gain and aperture efficiency of 20.6 dBi and 29%, respectively. The NFTS has an overall weight of 335g and a maximum height of 37 mm, as shown in Fig. 1. The composite dielectric semi-planar NFTS [3] later replaces the bulky NFTS, resulting in a 43% lower profile and 25% less weight, but without compromising antenna performance. However, these so-called first-generation (1G) all-dielectric NFTSs require expensive and sophisticated machining tools and techniques for fabrication.

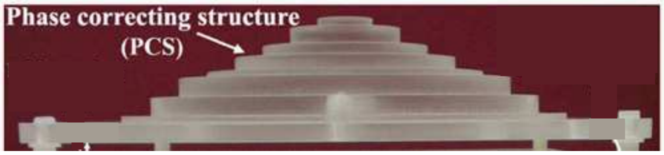

Fig. 1. An all-dielectric near-field phase correcting structure [2].

The 3D printed technology advanced the 1G NFTSs even further by using low-cost tailored dielectrics and in-house rapid prototyping facilities. The dielectric constant can be modulated simply by varying the in-fill percentage, resulting in a planar permittivity gradient all-dielectric NFTS [4]. It contributes ≈50% 3-dB directivity bandwidth of a compact ERA with only a material cost of 0.41 USD. The concept was further explored by designing a pair of NFTSs with a linear phase progression along its major axis [5]. Each NFTS is thick but demonstrates a comparable antenna beam steering performance in the elevation and azimuth planes.

III. COMPOSITE NFTSS

The second-generation (2G) NFTSs was realized by adopting the PCB technology. They are flat and planar, with many finer metallic inclusions strategically printed on multi-layer μWave substrates, as shown in Fig. 2. The composite NFTS proposed in [6] has 91% and 43% smaller profile and weight, respectively, than the 1G NFTS proposed in [2]. It improves the antenna directivity by 8 dB (from 12.5 to 20.5 dB). Subsequently, a pair of thin NFTSs was also presented to successfully demonstrate a non-tilted passive beam-steering antenna system [7]. These NFTSs are only ≈3.14 mm thick and have two dielectric and three metallic layers. Following Risley prism physics, the latter can steer the antenna beam up to $\pm 51^\circ$ in the elevation plane without any active RF components. The proposed technology enables flat-panel low-powered, fixed-volume beamforming antenna technology for mobile satellite communication (SatCom) applications.

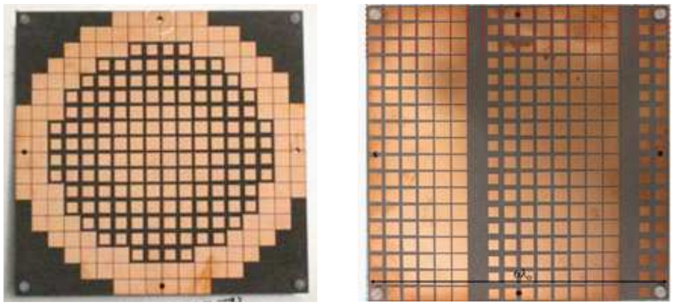
(a) (b)

Fig. 2. Composite NFTSs for (a) high-gain [6] and (b) passive beam-scanning [7] antenna systems.

IV. ALL-METAL NFTSS

Dielectrics require special consideration in some applications, such as in space and high-power microwaves, due to their added cost, weight, and unexpected dielectric properties (breakdown, ionization, cryogenic temperature issues). A completely new design technique was revealed as a third-generation (3G) NFTSs, where dielectrics are entirely eliminated. Wideband gain improvement and beam steering functions have been proposed using mechanically robust and electrically highly transparent all-metal NFTSs [8], [9]. As shown in Fig. 3, narrow slots are selectively cut in a monolithic thin metal sheet utilizing low-cost metal cutting technology. This slot-based design exploration of all-metal NFTSs reduces overall cost and weight while also making it best suited for future space-borne and high-power systems. The antenna performances are comparable as well; for example, the antenna prototyped in [8] obtained 12% 3-dB gain bandwidth, 46% impedance bandwidth, and an increased peak gain of 9.4 dBi (from 10.7 to 20.1 dBi). The thickness and weight of NFTS used with this antenna are $0.56\lambda_0$ and 150g, respectively. As demonstrated in Fig. 3(b), the method was also used to construct a linear phase progressive all-metal NFTS that locally manipulates the near-field phase to steer the antenna beam 23°off broadside direction [9] in the elevation plane.

V. CONCLUSION

The development of NFTSs compatible with a wide range of antennas is a considerable development in enhancing radiation characteristics of antennas while maintaining a low profile. The research has progressed through at least three generations, from a proof of concept design to more practical solutions addressing cost and large scale development. The 3D printed technology can allow quick and low-cost in-house prototyping with customized dielectric materials. Thin flat-panel-type NFTSs were realized using standard printed circuit technology. Recent research has been focused on completely eliminating dielectrics and expensive RF laminates for future mobile SatCom terminals that need low-cost and lightweight solutions both for high-gain and two-dimensional beam-steering antenna technology.

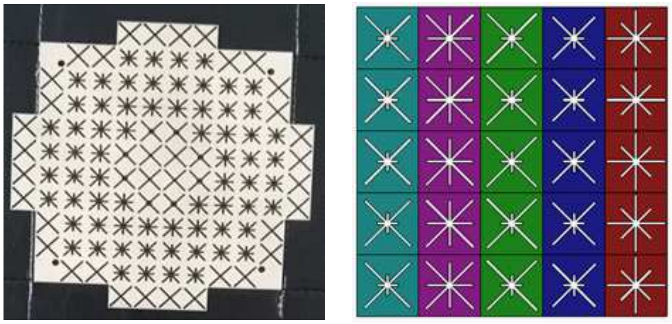
(a) (b)

Fig. 3. All-metal NFTSs for (a) wideband high-gain [8] and (b) passive beam-steering [9] antenna systems.

REFERENCES

[1] S. D. Targonski, "A Multiband Antenna for Satellite Communications on the Move," *IEEE Trans. Antennas Propag.*, vol. 54, no. 10, pp. 2862–2868, 2006.

[2] M. U. Afzal, K. P. Esselle, and B. A. Zeb, "Dielectric Phase-Correcting Structures for Electromagnetic Band Gap Resonator Antennas," *IEEE Trans. Antennas Propag.*, vol. 63, no. 8, pp. 3390–3399, Aug. 2015.

[3] M. U. Afzal, K. P. Esselle, and A. Lalbakhsh, "A Methodology to Design a Low-Profile Composite-Dielectric Phase-Correcting Structure," *IEEE Antennas Wirel. Propag. Lett.*, vol. 17, no. 7, pp. 1223–1227, 2018.

[4] T. Hayat, M. U. Afzal, F. Ahmed, S. Zhang, K. P. Esselle, and Y. Vardaxoglou, "Low-Cost Ultrawideband High-Gain Compact Resonant Cavity Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 19, no. 7, pp. 1271–1275, 2020.

[5] T. Hayat, M. U. Afzal, F. Ahmed, S. Zhang, K. P. Esselle, and J. Vardaxoglou, "The Use of a Pair of 3D-Printed near Field Superstructures to Steer an Antenna Beam in Elevation and Azimuth," *IEEE Access*, vol. 9, pp. 153 995–154 010, 2021.

[6] M. U. Afzal and K. P. Esselle, "A Low-Profile Printed Planar Phase Correcting Surface to Improve Directive Radiation Characteristics of Electromagnetic Band Gap Resonator Antennas," *IEEE Trans. Antennas Propag.*, vol. 64, no. 1, pp. 276–280, Jan. 2016.

[7] M. U. Afzal and K. P. Esselle, "Steering the Beam of Medium-to-High Gain Antennas Using Near-Field Phase Transformation," *IEEE Trans. Antennas Propag.*, vol. 65, no. 4, pp. 1680–1690, Apr. 2017.

[8] F. Ahmed, M. U. Afzal, T. Hayat, K. P. Esselle, and D. N. Thalakotuna, "A Dielectric Free Near Field Phase Transforming Structure for Wideband Gain Enhancement of Antennas," *Sci. Rep.*, vol. 11, no. 1, pp. 1–13, Jul. 2021.

[9] F. Ahmed, T. Hayat, M. U. Afzal, A. Lalbakhsh, and K. P. Esselle, "Dielectric-Free Cells for Low-Cost Near-Field Phase Shifting Metasurfaces," in *2020 IEEE Int. Symp. Antennas Propag. North Am. Radio Sci. Meet. Proc.*, 2020, pp. 741–742.