Guest Editorial
Low-Cost Wide-Angle Beam-Scanning Antennas

I. Introduction

ONE of the key antenna requirements in many modern wireless systems for communications and sensing is wide-angle beam-scanning [1]. The traditional method to achieve wide-angle beam-scanning is to employ mechanically controlled reflectors or lenses, which are bulky, heavy, and suffer from slow beam scanning speed. Other important limitations of mechanical scanning antennas include the lack of multi-beam scanning capability and the ability to conform with non-planar structures (conformal geometries), which are essential in a number of emerging systems requiring very low-profile antennas. An alternative technique is to employ electronically beam-scanning antennas using passive or active phased arrays [1]. Main disadvantages of phased arrays are high complexity, high power consumption, and high cost due to a large number of radio frequency (RF) or microwave phase shifters and T/R modules required. The problems worsen for phased arrays at millimeter-wave, sub-THz, and THz frequencies, due to significant losses in phase shifters and feed networks at higher frequencies combined with lower efficiency of power amplifiers [2]. The digital beamforming approach is even more costly and energy hungry due to the employment of large number of RF modules and digital devices [1], [3], [4].

For civilian applications, it is critical to develop low-cost wide-angle beam-scanning antenna technologies. Low-cost wide-angle beam-scanning antennas would have a wide range of applications such as base stations for mobile communications and 5G/B5G/6G mobile phones or user terminals (UEs), mobile terminals for satellite communications on the move, automotive radars, imagers, small satellites, Internet of Things, and Internet of Space. To meet the market needs, a number of techniques have been developed in recent years to deliver low-cost wide-angle beam-scanning antenna solutions. The most widely known one beyond the antenna community is hybrid antenna arrays in which passive antenna beamforming, active analog beamforming, and digital beamforming are combined to lower the overall system cost with minimum performance degradation [4]. Although hybrid antenna arrays may have limited scanning range due to the use of subarrays, this drawback can be overcome by employing non-conventional subarrays such as lens antennas. Other pure antenna solutions include 1-bit reconfigurable reflectarrays [5], planar substrate-integrated-waveguide-based leaky-wave beam-scanning antennas [4], [6], small-director-array-based beam-steerable antennas [6], and active-frequency-selective-surface-based 3D beam-scanning antennas [7]. Some methods are summarized in [8].

The purpose of this Special Issue is to draw attention to the latest progress in the theory, design, development, measurements, and in-field deployment of low-cost wide-angle beam-scanning antennas for a wide range of current and emerging applications. These range from base stations of mobile communications networks, mobile phones, mobile terminals for satellite communications on the move, and small satellites (Cube-Sat, Micro-Sat, Mini-Sat, Nano-Sat, Pico-Sat) to sensing and Internet of Things.

II. Main Contributions of the Papers in This Special Issue

This Special Issue on low-cost wide-angle beam-scanning antennas has attracted great interest from the antennas research community. Through a rigorous review process, thirty papers have been selected to present the state of the art research across the globe. These papers address the special issue theme from various angles, from fundamental technology innovation to new functionalities. The papers are clustered in the following seven categories: 1) circular polarization and dual polarizations, 2) wideband and multiple bands, 3) transmitarrays and lenses, 4) irregular array architecture, 5) multi-beam antennas and beam-forming networks, 6) frequency scanning, and 7) novel radiating elements, phase shifters, deployable antennas, and pattern reconfigurable arrays.

A. Circular Polarization (CP) and Dual Polarizations

In [A1], Lou *et al.* report a low-profile circularly-polarized beam-scanning planar antenna which employs a patch array fed by the coupling slots of parallel plate waveguides. Beam scanning of $\pm 40^\circ$ is achieved by rotating the circular plate. A new impedance matching method is also introduced to suppress the open stopband. The antenna has a simple structure and consists of only three substrate layers. The technique can be easily extended to large-scale arrays for applications in satellite communications on the move.

In [A2], Wei *et al.* present a dual circularly polarized substrate integrated waveguide cavity-backed antenna with wide 3-dB Axial-Ratio beamwidth. Right-hand CP or left-hand CP radiation can be produced by exciting different input ports. One 8-element linear array is designed and demonstrated to operate at Ku band and achieves beam scanning from -59° to 58° at dual CP status.

In [A3], Zhang *et al*. report a concept of dual-polarized reconfigurable reflectarray (RRA) featuring dual-polarized

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beam control based on a dual-channel programmable metasurface. PIN diodes are integrated into each metasurface element as the active components for providing independent phase control in two orthogonal polarization channels. One RRA prototype with 20 × 20 elements is fabricated and measured, and the antenna achieves wide-angle beam scanning of ±40° at 7.45 GHz, and peak gains of 21.13 dBi and 20.89 dBi in dual channels.

In [A4], Polo-Lopez *et al.* propose an evanescent quadridge antenna to conceive dual-polarized full metal front-ends for applications in active phased array antennas with wide field-of-view. A design methodology is developed that allows to induce radiation from subwavelength squared apertures based on the use of evanescent and quadridge waveguides. The methodology is illustrated by one antenna design at 14.25 GHz, which achieves 4.5% bandwidth, dual CP radiation, and beam scanning of ±50°.

In [A5], Yang *et al.* present a wideband dual-polarized wide-angle scanning phased array antenna for 5G mobile communications. To reduce the mutual coupling between adjacent unit elements in the array, a current cancellation method is developed by changing the current distribution on the excited unit element to induce a pair of canceling currents on the adjacent unit element. Such a current distribution also broadens the beamwidth of the unit element. A dual-polarized phased array at C band is designed and demonstrated to achieve beam scanning of ±60°.

B. Wideband and Multiple Band Antennas

In [A6], Xiang *et al.* report a wideband 1-bit reflectarray antenna with two-dimensional electronically beam-scanning capability. The wideband RRA is based on the magnetoelectric (ME) dipole antenna as elements. Each element is integrated with only one PIN diode to change the types of resonances, which leads to a reconfigurable reflecting phase with a 1-bit resolution. One RRA having 16 × 16 elements is designed and the measured results confirm that the RRA achieves a 3 dB gain bandwidth of 38.4% with a peak aperture efficiency of 24% at 12 GHz, and a beam-scanning range from −60° to +60° in the E-plane and 0° to +60° in the H-plane within the whole operating bandwidth.

In [A7], Sun *et al.* report a 2 GHz to 18 GHz ultra-wideband phased array antenna with low profile, low radar cross section and cylindrically conformal shape. To achieve both ultra-wideband operating frequency bandwidth and low profile, the distributed capacitance structure to avoid inducing the parasitic loop mode is added into the feeding balun. A folded metasurface is employed to increase the beam-scanning range while improving the impedance matching bandwidth. Orthogonally polarized slots are etched on the folded metasurface so that the 0º/180° reflection phase for the orthogonally-polarized incident waves can be obtained. One 19 × 19 prototype phased array is fabricated and the measured results demonstrate that the antenna can operate from 2.0 GHz to 18.0 GHz, has a low profile of only 0.06 λ (λ at 2.0 GHz), a cylindrical conformal shape, and a beam-scanning range of ±60° at maximum active VSWR of 4.8.

In [A8], Wang *et al.* propose a dual-band fixed-frequency beam-scanning printed leaky-wave antenna with large frequency ratio. Microstrip lines and a gap waveguide are employed to feed the low and high frequency patches, respectively. The operation state of each patch can be switched on or off electronically by controlling the PIN diodes. The hologram is generated on the radiating aperture of the leaky wave antenna, which can be electronically manipulated to produce fixed-frequency beam scanning. A dual-band beam-scanning antenna operating at both C and Ka bands is designed and demonstrated to achieve beam scanning of ±50° at both bands.

In [A9], Ding *et al.* propose a Ku-/Ka-band shared-aperture phased array antenna which consists of one 8 × 8 Ku-band vertical-polarized dipole array antenna fed by a microstrip line to stripline transition and one 8 × 8 Ka-band horizontal-polarized waveguide antenna array fed by a microstrip line/substrate integrated waveguide/fin-line transition. The antenna is demonstrated to achieve a wide impedance bandwidths of 25% in the Ku-band and 11.4% in the Ka-band, scanning angles of ±60° at 14 GHz, ±50° at 16 GHz, and ±35° at 18 GHz, and ±40° at 33 GHz, ±40° at 35 GHz, and ±35° at 37 GHz in both E- and H-planes, respectively. Such an antenna is promising for applications in multi-band shared-aperture radar systems.

In [A10], Chang *et al.* present a co-design method for designing a low-profile CP array antenna consisting of a circular polarizer in the near field of a linearly-polarized array antenna. To improve the CP scanning range, the polarizer adopts a co-design partition scheme instead of repeated units. One K/Ka band shared-aperture phased array antenna is then designed and demonstrated to obtain right-hand circular polarization from 19.7 GHz to 20.2 GHz and left-hand circular polarization from 29.5 GHz to 30 GHz, and the axial ratio is below 4 dB in the scanning range of ±55° at K band ±60° at Ka band.

C. Transmitarray and Lens

In [A11], Wang *et al.* present an electronically beam-scanning transmitarray employing a new reconfigurable dual-layer Huygens element. The Huygens element consists of two metallic crosses printed on both sides of a dielectric substrate, enabling a near non-reflection Huygens resonance. A 1-bit phase compensation with low transmission loss is achieved by controlling two PIN diodes on the radiating element. The element has a much simpler structure compared to other reported transmitarray elements, and is promising for applications in large-aperture transmitarrays at higher frequencies. One transmitarray at Ku band is designed and demonstrated to achieve 2-D beam scanning beams within ±50° in the E-plane and ±40° in the H-plane with a maximum realized gain of 18.4 dBi.

In [A12], Garcia *et al*. propose a beam-scanning parallel-plate waveguide fan-beam lens antenna based on a novel compound gradient index (GRIN) lens approach. The measured results of lens antenna demonstrate the beam scanning to ±48° with an average maximum scan loss of 2.7 dB over the Ka-band. The lens achieves a high radiation efficiency of 92% and a maximum gain of 22.8 dB while using only 37.3% of the GRIN material required for a comparable Luneburg lens.

D. Irregular Array Architecture

In [A13], Zhang *et al.* propose an electronically reconfigurable reflectarray antenna with radiating elements in hyperuniform disordered distribution. Such an irregular distribution of radiating elements enables a significant reduction of radiation elements and active devices while simplifying the control networks for active devices. A 1-bit reflectarray with 64 elements in hyperuniform disordered distribution is designed and demonstrate to achieve 36% reduction of the number of active devices, compared to a 100-element periodically-distributed reflectarray with similar performance. A beam scanning range of $\pm 50^\circ$ is achieved.

In [A14], a subarray partitioning scheme based on Penrose tessellation is proposed by Dicandia *et al.*. The regular triangular lattice adopted for the arrangement of the antenna elements is organized into irregularly shaped tiles by exploiting the aperiodic properties offered by the Penrose tessellation. Such an array architecture enables a significant reduction of the transmit/receive modules in active phased arrays while achieving wide scanning angle and low sidelobe levels, thanks to the design process based on the Pareto front optimization which is able to tackle conflicting objectives. The method is promising for reducing the power consumption in wide-angle beam-scanning phased array antennas.

In [A15], Zeng *et al.* propose a square-rate arrangement method to suppress the grating lobes in the planar phased array with large element spacing. After analyzing the appearance of grating lobes in rectangular- and parallelogram-lattice arrangements, a new square-rate arrangement method is proposed, in which the specific position of the square-rate array is deduced to homogenize the grating lobes. The presented method is verified by an 8×16 array with interelement spacing of one wavelength. The measured results show that the antenna beam can be steered up to $\pm 75^\circ$ in E-plane and $\pm 27^\circ$ in H-plane with the sidelobe levels below -10 dB within the entire two-dimensional scanning volume. Compared with the uniform array configuration, nearly 40% of T/R modules are reduced.

In [A16], Laue *et al.* report the design and analysis of a checkered-network compressive array with integrated antenna elements and demonstrate that compressive arrays are promising for reducing the number of controls in beamforming networks. It shows that steered-beam squint is a greater issue than previously assumed, and design guidelines are provided for minimizing the risk of excessive steered-beam squint in manufactured compressive arrays.

E. Multi-Beam Antennas and Beam-Forming Networks

In [A17], Guo *et al.* report a novel concept, the generalized joined coupler (GJC) matrix, which encapsulates both the Blass matrix and the Nolen matrix as well as its new variants described in the paper. They also present a theoretical framework for generating multiple individually and independently controllable beams using the GJC matrix. The paper presents a matrix theory of and an optimization algorithm for synthesizing such matrices and, consequently, the phased multiple beams. Numerical simulation results demonstrate that phased multiple beams with independent control of individual beam directions and sidelobes can be synthesized in a systematic manner.

In [A18], Cheng *et al.* present a 94 GHz multi-beam antenna using the binary phase-controlled concept. The feeding network consists of four unconnected layers, and the ridge or groove gap waveguides are adopted as the guided wave structures. A key planar gap waveguide Magic-Tee is designed to obtain 0° and 180° phase states and then integrated with an 8×8 slot array antenna for achieving multiple beams. The 8×8 slot array antenna can electronically switch among one-beam and three different dual-beam states pointing to $\pm 7^\circ$, $\pm 17^\circ$, and $\pm 38^\circ$, respectively. The antenna has a simple structure and low cost for manufacturing, and is promising for millimeter-wave multiuser communication.

In [A19], Cao *et al.* report a dual-polarized multi-beam antenna based on a pillbox reflector beamforming network (BFN). The antenna consists of two CNC milled pillbox reflector-based BFNs, one 3D-printed ridged waveguides-based shared-aperture dual-polarized slotted waveguide antenna, and two feed sources using patch arrays. The feed sources at different positions of the focal plane can produce beams at different directions. The dual-polarized radiation is realized by the dual-polarized slotted waveguides excited by the two BFNs at the sides of the antenna. One dual-polarized antenna at 10 GHz is designed and demonstrated to achieve $\pm 36^\circ$ beam scanning in the multibeam plane with the minimum crossover level of -2.1 dB.

In [A20], Zhu *et al.* propose a new approach using planar hybrid couplers and phase shifters to design wideband 6×6 BFNs for producing multi-beams. The new type of wideband hybrid coupler is developed using a slotline resonator and microstrip-to-slotline transitions, and can obtain high isolation between the sum and difference ports. Two wideband 6×6 BFNs are designed to generate five and six beams, respectively. A prototype of multi-beam antenna over a wide frequency range from 3.12 GHz to 4.65 GHz is designed, manufactured, and measured.

F. Frequency Scanning

In [A21], Yang *et al.* present a low-profile millimeter-wave frequency-scanned CP array based on wideband circularly polarized aperture-coupled magneto-electric dipoles (MED). The MED is printed on two dielectric substrate layers. The electric dipole consists of two metal patches with perturbation structure, while the magnetic dipole consists of two rows of metal vias passing through the top substrate layer. A new compact wideband transition from the rectangular waveguide to the substrate integrated waveguide (SIW) is employed as the feed source for the CP array. A slow wave structure is etched on the ground of SIW to widen the beam scanning range. One 16-element array is designed and the measured results demonstrate a beam-scanning range from -34° to $+22^\circ$ when the frequency is changed from 23 GHz to 33 GHz.

In [A22], Li *et al.* report a high-gain CP leaky-wave antenna for CubeSat communications. The proposed LWA is implemented by etching periodic fan-shaped slots on top of an SIW, and these fan-shaped slots produce CP radiation with high efficiency over a wide frequency range. One SIW LWA prototype is designed and the measured results demonstrate LHCP/RHCP beams steerable from −51° to 0° or from 51° to 0° in the elevation when the frequency varies from 27.4 GHz to 37.3 GHz. One conformal CP array with high gain is also introduced by combining the CP radiation of two LWAs deployed in two perpendicular surfaces of one cubic unit (1U) CubeSat, leading to a high gain of 16.6 dBi.

In [A23], Huang *et al.* propose a printed comb-line leaky-wave antenna for null-scanning across a frequency band. The antenna consists of a microstrip line and two groups of stubs loaded on both sides. The two groups of stubs, placed periodically with two slightly different periods, provide two different space harmonics that contribute to two radiation beams. The demonstration of one antenna design achieves a wide null-scanning range from −38° to 40° with a null depth below −24 dB in a frequency band from 9.9 GHz to 13.8 GHz.

G. Novel Radiating Elements, Phase Shifters, Deployable Antennas, and Pattern Reconfigurable Antennas

In [A24], Chen and Wu propose a cross-polarization (X-pol) suppressed probe-fed patch antenna element for a wide-angle beam-scanning phased array design. The X-pol radiation in H-plane of the patch antennas is suppressed by introducing two or more floating metal cylinders underneath the air-filled patch, where the X-pol is canceled by the radiation from induced currents on metal cylinders. The X-pol level of antenna can be suppressed to be below −49 dB and −37 dB theoretically and experimentally for $|\theta| \leq 60°$. An 8-element array is demonstrated to achieve the beam scanning angle of ±40°, while that of the conventional patch array is about $|\theta| \leq 12°$ only.

In [A25], Wang *et al.* report a pattern-reconfigurable monopole-like Huygens radiating element for wide-angle beam-scanning phased arrays. A miniaturized broadband hybrid metasurface with a compact size of $0.28\lambda \times 0.28\lambda \times 0.11\lambda$ is developed by combining a dielectric resonator and 3 × 3 mushroom-like metasurface. By exploring the monopole-like Huygens radiation mechanism, a pattern-reconfigurable hybrid metasurface antenna is produced and it can be electronically switched between one broadside and two tilted ($\theta = \pm 40°$) modes. A five-element linear array using the reconfigurable elements is designed and demonstrated to operate from 3.30 GHz to 3.80 GHz and achieve beam scanning of ±70°, promising for 5G multibeam base station and microcell applications.

One classic problem of phased array antennas is that the gain drops when the beam scans towards a wide angular range. In [A26], Su *et al.* present an alleviating technique based on a gain-compensating approach. The element pattern is optimized in such a way that the element gain is nearly inversely proportional to the peak gain of the array factor. Hence, the peak gain of the overall array antenna is kept almost the same over a wide-scanning range. One 9-element cylindrical dielectric resonator antenna array at X band is designed and demonstrated to achieve nearly constant antenna gain over its H-plane beam-scanning range of ±72°.

Microwave phase shifters are key components in phased arrays. In [A27], Yuan *et al.* report a varactor-based phase shifter operating in differential pair for wide-angle beam-scanning phased array antenna applications. The basic phase-tuning unit consists of a microstrip transmission line and several shorted-stub-terminated varactors loaded on its edge. A pair of phase-tuning units, each including three stub-loaded varactors, is designed to produce a continuously tunable phase difference nearly covering 0°–360° with a low maximum insertion loss of 2.04 dB. A 1 × 4 dielectric resonator antenna array is designed and demonstrated to achieve continuously beam scanning from −45° to 45°, with a tuneable operating frequency band from 4.75 GHz to 5.25 GHz.

In [A28], Cui *et al.* present a 3D-printed "Kirigami"-inspired deployable beam-scanning dielectric reflectarray, which is promising for millimeter-wave applications such as 5G and satellite communications. The design is enabled by a series of "Kirigami"-inspired two-stage snapping-like element structure that can be retracted by 66% to save space. The prototype is fabricated with stereolithography 3D printing. A bi-focal phase distribution method is utilized to optimize the RF performance of the array, and achieves beam scanning from −30° to −10° and 10° to 30°. The uniqueness of the antenna includes beam-scanning ability, deployability, and dielectric-only design.

In [A29], Zhang *et al.* propose a low-profile vertically polarized planar endfire smart antenna that can achieve 360° beam-steering and high beam-shaping capability. Based on small director array approach in [6], a planar antenna with lower profile and using one single substrate is developed. The microstrip antenna is printed on a single thin substrate with a vertically polarized omnidirectional driven source and 36 tuneable slot-integrated microstrip vertically polarized resonators for shaping the endfire beams. The prototype antenna demonstrates that it can operate from 5.55 GHz to 5.75 GHz and scan a single endfire beam from 0° to 360° in the azimuthal plane.

In [A30], Chen *et al.* report a low-profile planar phased array with wideband filtering response and wide-angular scanning behavior. The filtering response with harmonic suppression is integrated into a single-layer array, enabling a reflection bandwidth from 4.6 GHz to 5.3 GHz and two radiation nulls at the upper and lower band edge of the reflection curve. In addition, a circular patch loaded with parasitic monopole approach is utilized to achieve ±60° scanning with low sidelobe levels in its E-plane.

III. Conclusion and Acknowledgment

Low-cost wide-angle beam-scanning antenna is a very challenging research topic with huge potential of wide applications in wireless communications and radar systems. We hope the papers in this Special Issue will enrich the knowledge of readers and researchers, and stimulate new research activities. We sincerely thank all the authors and reviewers for their contributions, and also the Editor-in-Chief and Staff Members of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION for their constant support over the entire process from the proposal-making to the final publication.

Sadly, Professor Ali Safavi-Naeini passed away in October 2021. Prof. Safavi-Naeini was a pioneer in the field of low-cost phased arrays, and he actively supported the launching of this Special Issue as a Guest Co-Editor. Although he is no longer with us, his legacy and spirit will undoubtedly live in the hearts and minds of hundreds of students he taught and mentored, as well as many colleagues he inspired.

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APPENDIX: RELATED ARTICLES

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