Traveling-Wave Antenna Array (TWAA) -a Multioctave Planar Phased Array (MPPA)*

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***Abstract*—This paper demonstrates and characterizes the Traveling-Wave Antenna Array (TWAA) as a Multioctave Planar Phased Arrays (MPPA) capable of efficient wide scan with low cross polarization. Three brassboard TWAA panels having 16×16 elements were fabricated and tested for wide-angle scan up to 60° off broadside over 2-12 GHz using a True-Time Delay (TTD) Beam Steering Network (BSN) in a corporate feed configuration. Fairly good performance was exhibited using conventional far-field antenna range tests in an anechoic chamber. The test data are in fair agreements with computer simulation data generated by The Ohio State University. This study appears to be the first time that an MPPA is demonstrated to be capable of multioctave bandwidth for efficient 60° scan in a full-fledged manner with convincing direct calibrated measurements and consistent with calculated data. The state-of-the-art, and some ambiguities and controversies, in this field of MPPAs are also reviewed with comments and clarifications.**

***Index Terms*—array, phased array, planar array, broadband antenna, traveling wave antenna, traveling wave array, ultrawideband antenna, conformal array.**

I. Introduction

RESEARCH in Multioctave Planar Phased Arrays (MPPA) promising multioctave bandwidth and wide-angle scan has become increasingly active since 1980s, and accelerated exponentially since 2000 [1]-[3]. Unfortunately, except for those of flared-notch elements, their demonstrations have been mostly by indirect and/or incomplete methodologies, generally stopped at the stage of numerical simulation of an infinite planar array and measurements using the Scan Element Gain (SEG) patterns of a rather small empirical model (8×8 elements or fewer). Such practice is common in feasibility studies, driven by the technical difficulties and extremely high costs in implementing multioctave feed and beam scan mechanisms needed for the test of MPPA.

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However, this common practice has severe limitations, as has been pointed out by Hansen [3] and this author [4]-[5]. Its pitfalls climaxed during 2015 IEEE International Symposium on Antennas and Propagation in Vancouver, Canada. In an Industry Special Session on the first day of the Symposium, Prof. Neto [6] elaborated and clearly concluded in his 40-minute presentation that, based on 13 years of research, *the realistic goal for Connected Arrays is limited to a bandwidth of 30% to 60% (1 octave) if efficient scans to 60° with cross-polarization (X-pol)<-10dB are required*. (Connected Array refers to an MPPA approach spearheaded by researchers of Raytheon Company and its collaborators such as Neto [2]-[3], [6].) This conclusion was so surprisingly different from this author's impression on the state-of-the-art of MPPA and his poster-session paper in this Symposium [7] that he spontaneously voiced strong objections.

The ensuing dialogues among this author, Prof. Neto, and other attendees in the Symposium were instrumental in encouraging this author to formally publish his symposium paper [7] and clear up some ambiguities and controversies in the interest of "science" and "truth" vigorously sought in their dialogue and email exchanges.

II. History and State-of-the-Art of Multioctave Planar Phased Arrays (MPPA)

The history and the state-of-the-art of MPPA were succinctly summarized in [6]. But the following clarifications, updates and observations are in order:

1. The bandwidth (BW) of a system or device, such as MPPA, depends on its criteria or definition. *The three Key Performance Parameters (KPP) set down in [6] to define bandwidth for MPPAs are not stringent except for the scan angle.* The KPP of being "efficient" is a very loose word, but obviously it rules out the use of lossy materials such as ferrites. The KPP of "scan to 60°" is an ideal yet demanding goal for most of the applications. For example, to cover full 360° azimuthal with four MPPAs, one on each of the four surfaces of a rectangular pyramidal platform, conventional KPP of ±45° scan for each MPPA is not sufficient. Yet KPP of ±55° scan may

be acceptable. The KPP of X-pol<-10dB is too lenient, it is obviously an expedient choice driven by current performance limitation as shown in PPT slide #53 of [6].

2. Obviously [6] has excluded MPPAs that were demonstrated only by indirect and/or incomplete methodologies; and rightfully so. This explains why this author's Traveling-Wave Antenna (TWA) Array (TWAA), being developed at Wang Electro-Opto Corporation (WEO) [4]-[5], was not included in its discussions. From another perspective, we can say that [6] recognizes only MPPAs at Technology Readiness Level (TRL) of 6 or higher, thus excluded TWAA as it was at TRL-3 and TRL-4 according to [4] and [5], achieving only feasibility demonstration. Such a selection process is of course appropriate for the Industry Special Session in which [6] was presented. Indeed, history has plenty of examples in which a technology reached TRL-4 but later proved to be fundamentally deficient or even flawed. (This is obviously the same reasoning why Dr. Hansen has been skeptical of MPPAs [3].)
3. In this context of [6], by 2007 MPPAs consist of two approach/groups: (1) the "Connected Arrays" of Raytheon (J. J. Lee et al) and closely associated Neto group; and (2) the "Tightly Coupled Arrays (TCA)" consisting of Harris Corporation and The Ohio State University (OSU) team led by Prof. Ben Munk.
4. Since 2006 this author has led the development of TWAA [4], [5], [7]-[9]. While most researchers on MPPA credited Wheeler's Current Sheet Antenna (CSA) [10] in 1965 as their conceptual approach, this author has traced the embryonic root of TWAA [5] to Walter [11]. Now that TWAA has recently achieved TRL and MRL (Manufacturing Readiness Level) of 6 based on the full-fledged test results [7], it should be recognized as the third approach/group of MPPA.
5. Reference [6] called the TCA family as the Harris group/approach, apparently since Harris Corp. filed and owns all the relevant 18 patents [12]-[14]. Regarding "Chen, Sertel, Volakis" of OSU "enters" the TCA family around 2009 (PPT slide #39), they have since 2007 been continually participating in WEO's research under subcontracts. While holding on to the TCA heritage under research programs funded by other resources, e.g. [15]-[18], they have named their design approach as "Tightly Coupled Dipole Arrays (TCDA)" [17]-[18] to distinguish from the TCA of Harris/Munk.
6. PPT slide #55 indicated that OSU's TCDA also suffers this bandwidth limitation since they use similar feeds. Review on [17] confirmed this viewpoint as its scan is up to 45° only. And review on [18] revealed that its results were based on simulation and SEG measurement, which can only demonstrate up to TRL 3 or 4. It is also noted that TCDA designs have migrated away from the TCA of Harris patents and Munk publications, in which impedance matching relies primarily on substrate/superstrate and array elements are simple linear dipoles.

III. TWA ARRAY (TWAA)

The TWAA design has evolved from an 8×8-element model developed in 2011 and reported in 2013 [5], which were based on numerical simulation of an infinite planar array and measurements using the Scan Element Gain (SEG) pattern technique appropriate for feasibility study up to TRL 3 or 4. To advance to TRL-6 and MRL-6, three brassboard models were fabricated by standard commercial PCB (Printed Circuit Board) production processes. Fig. 1 shows photographs of the 2-12 GHz TWAA with 16×16 (256) elements, in front and back views, as reported in [7].

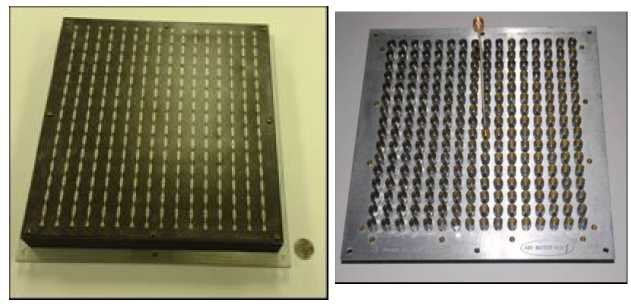

Fig. 1. Photograph of the TWAA in front and back views.

The design concept can be described in a unit-cell perspective, as discussed in [4], [5] and [7]-[9]. The element radiators of the planar array are planar closely-coupled wideband bowtie dipoles, with widths s and b at the feed region and the two ends, respectively, as shown in Fig. 2, for a unit-cell of the array. To suppress grating lobes, the length l and width w of the unit cell are chosen to be $\lambda_h/2$, where λ_h is the free-space wavelength at the highest operating frequency.

Fig. 3 depicts the cross-sectional view around a center element of a TWAA. Each dipole is capacitively coupled with adjacent dipoles at both ends (in the region of green color in Fig. 2) to facilitate Traveling-Wave (TW) propagation. The array center element radiator is fed by a transmission line which connects to an impedance-matched circuit leading to the feed network circuit contained inside a closed region below the ground plane. For systems integration, there is room of more than 1.27 cm in thickness below the ground plane (out of the 2.90-cm thickness) that can be used to accommodate T/R modules, BSN (Beam Steering Network), etc.

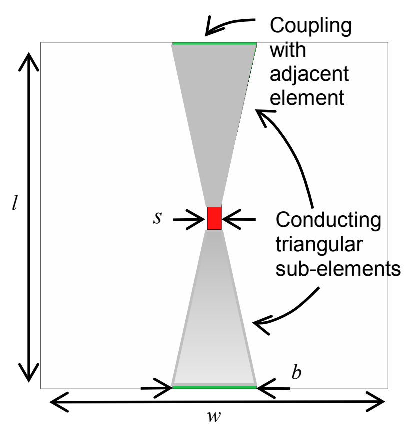

Fig. 2. Unit cell of planar TWA array with planar bowtie dipole element.

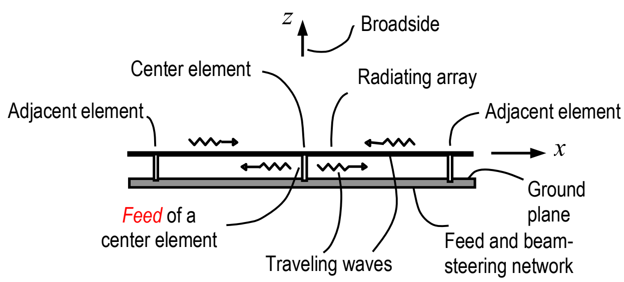

Fig. 3. Cross-sectional view around a center element of a TWAA.

IV. Empirical and Theoretical Characterization

The far-field test is the golden standard for antenna testing, most effective and even necessary for demonstration of a new antenna technology like MPPA that is particularly riddled with controversies. Far-field radiation performance based on a sufficiently large array provides data that are direct, reliable, and convincing. It is free from the uncertainties deeply ingrained in the complex and extensive data collection and processing involved in near-field and compact range tests.

Nevertheless, measurements using the Scan Element Gain (SEG) patterns were also used to see how well they correlate with the data of the full array. Fig. 4 shows the back of the array panel set up for SEG measurement, in which a center element is fed and tested while all other elements are terminated in 50-ohm loads. The results were satisfactory.

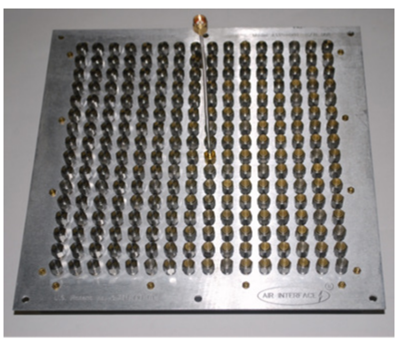

Fig. 4. Back of the array panel set up for SEG measurement.

As there was no known and available Beam Steering Network (BSN) that covers the 2-12 GHz bandwidth, a True-Time-Delay (TTD) BSN as a corporate feed was developed in-house. (A TTD BSN generates time-shift, instead of phase shift, thus can also demonstrate performance for digital signals.) Discrete TTD lines for beam scan at 0º, ±30º, ±45º, and ±60º made of phase-matched semirigid coaxial cables, combined by three stages of 2-18 GHz power dividers, constitute the BSN, which is reciprocal for both transmit and receive. Since such a BSN is very expensive and difficult to fabricate and set up, our research so far indicated that it has never been attempted by others for large arrays.

Fig. 5 shows the fully assembled array under far-field tests in WEO anechoic chamber. It includes the array panel of Fig. 1 and the BSN (the three banks behind it). As can be seen, a mounting structure is installed on the antenna tower to support and interface with the array system on the platform. The array's phase center, located at the center of the front surface of the array panel, is aligned with the axis of azimuthal rotation of the antenna tower.

Fig. 6 shows measured SWR for the array with BSN set at 0° scan (broadside). The results are very good; results at other scan angles are similarly good. Yet it is recognized that, due to the effects of the BSN, additional analysis and evaluation on the data are needed to obtain an accurate interpretation if needed. On the other hand, it is worth pointing out that, in systems application, impedance matching is an easier problem since it is often integrated into the feed network that includes the BSN, T/R module, etc., not in a corporate feed configuration, and without these SMA connectors.

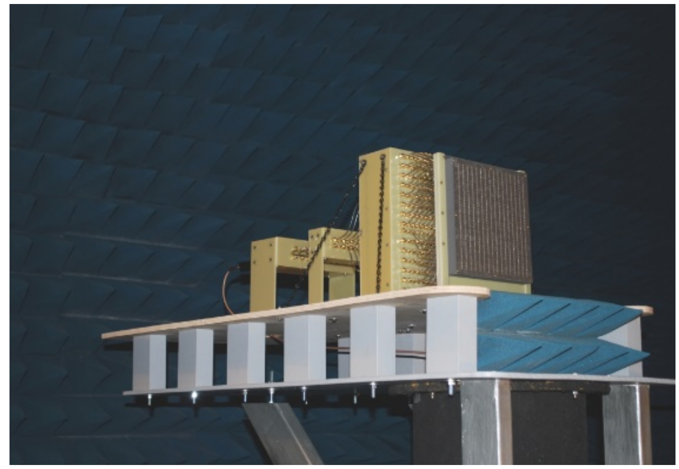

Fig. 5. A TWAA with three banks of TTD BSN being measured in WEO anechoic chamber.

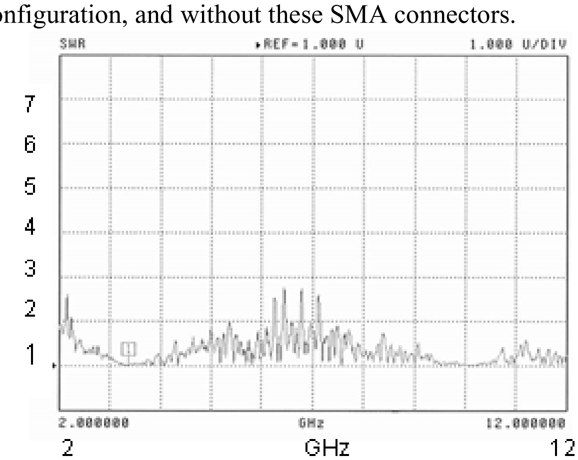

Fig. 6. Measured SWR for array with 0° scan.

Reference [6] revealed an important yet not widely known fact that radiation patterns, particularly their cross-polarization (X-pol), are the fundamental limitation for the bandwidth of existing efficient wide-scan MPPAs, including Vivaldi, stacked patch, connected arrays, TCA, or TCDA, etc. Therefore, a fairly complete test is needed to characterize TWAA's pattern performance. By the same token, fairly complete high-quality data are also needed for presentation.

Therefore, both *E* and *H*-plane gain patterns over 0º-360º for principal polarizations, covering 2-12 GHz at 0.25 GHz intervals, were measured in an anechoic chamber for array beam scan at 0º, ±30º, ±45º, and ±60º. Thus the data sampled are fairly dense throughout the large spatial and frequency domains. Fig. 7 and Fig. 8 show computed and measured *H*-plane and *E*-plane gain patterns, respectively, for scans at 0°, -30°, -45° and -60° off broadside at 2, 4, 8, and 12 GHz.

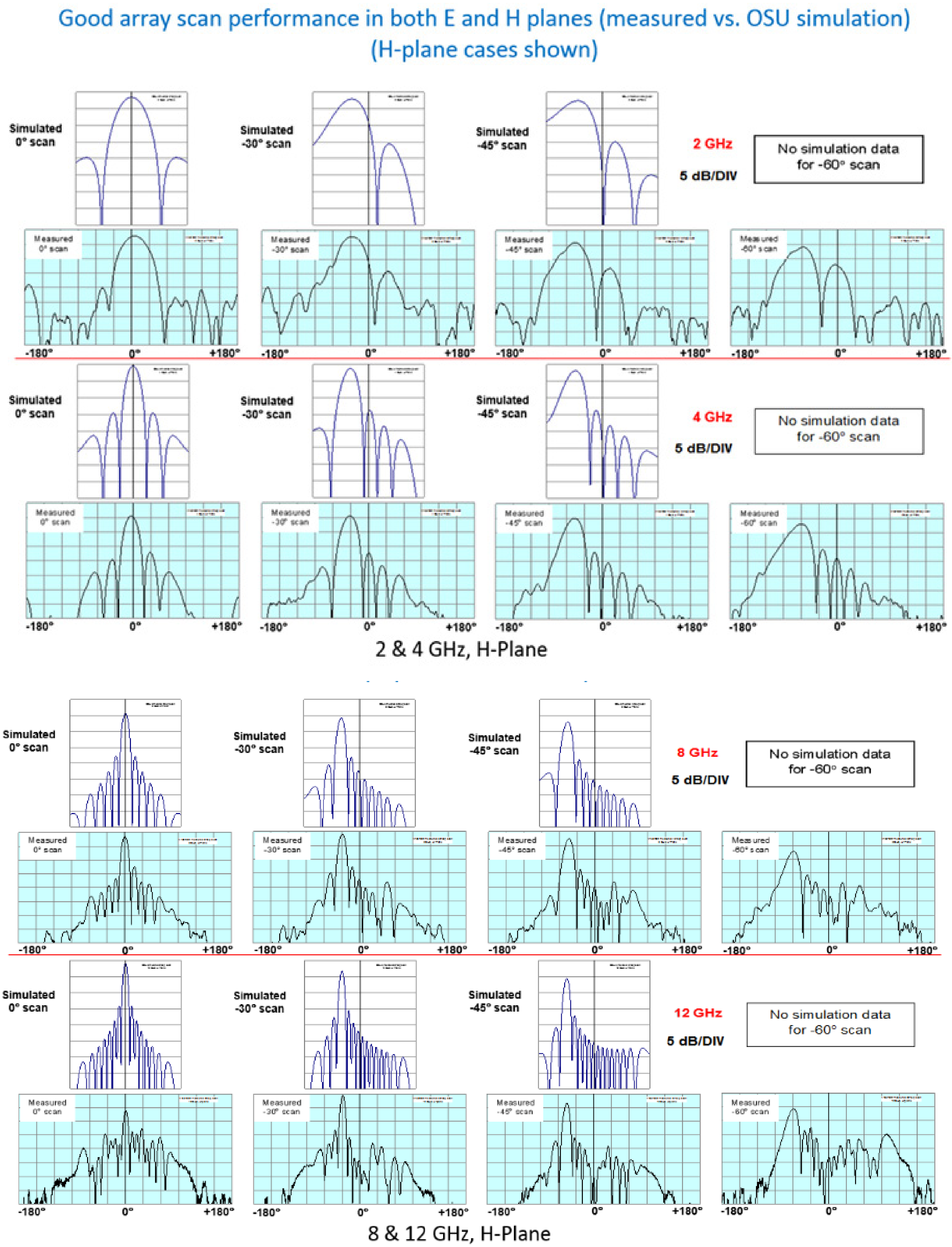

Fig. 7. Comparison of measured and simulated *H*-plane radiation patterns for scan at 0°, -30°, -45° and -60° off broadside at 2, 4, 8, and 12 GHz.

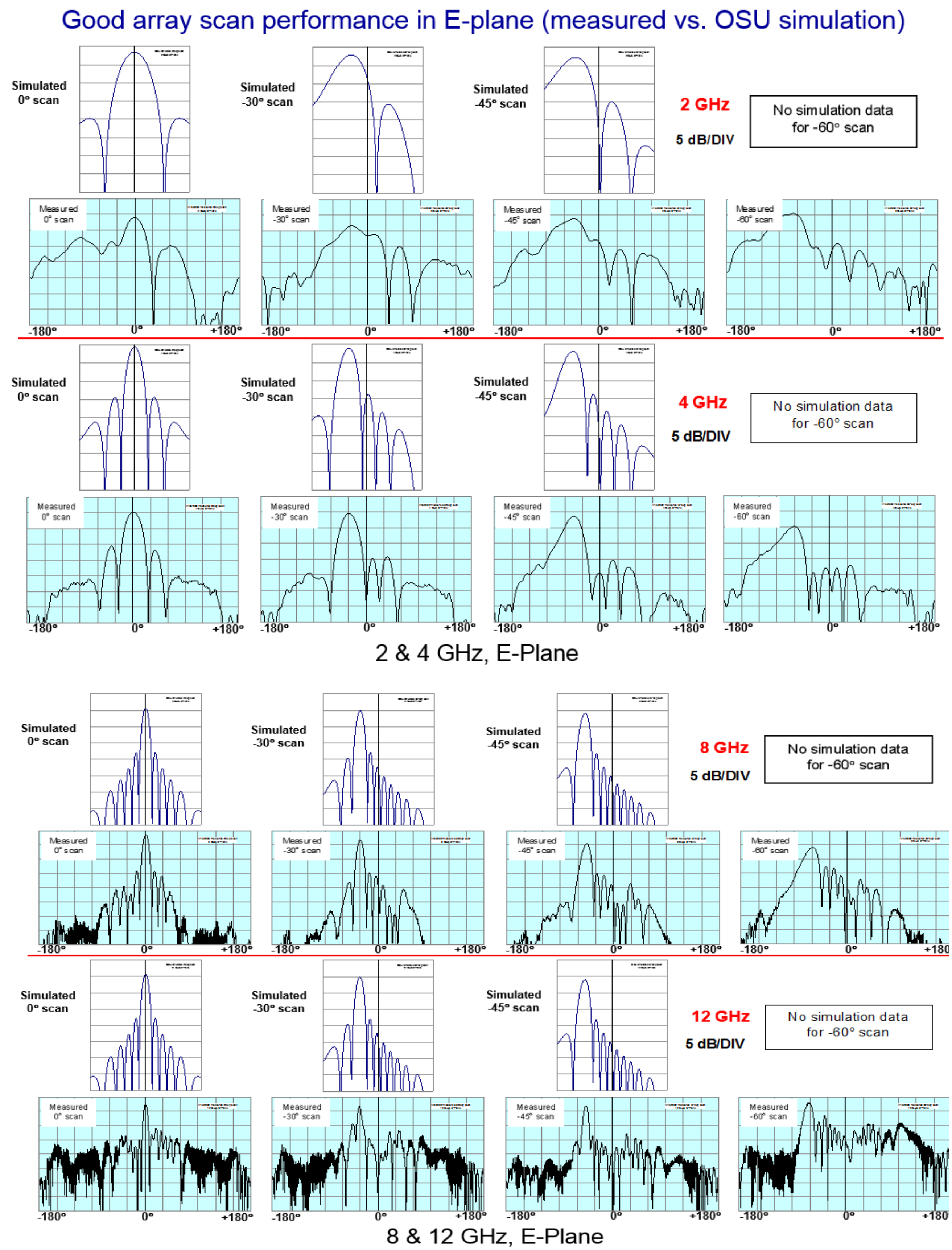

Fig. 8. Comparison of measured and simulated *E*-plane radiation patterns for scan at 0°, -30°, -45° and -60° off broadside at 2, 4, 8, and 12 GHz.

The computed gain patterns were generated at Electro-Science Laboratory (ESL) of The Ohio State University (OSU), fairly independently. The simulated patterns were obtained by multiplying the array factor and the computed Scan Element Gain (SEG) patterns of an infinite array, as instructed by the author, with a moment-method solution using commercial software.

In view of the controversies on the measurement of MPPA, e.g. [3], the author dictated that simulation at OSU be for the transmit mode and instructed on the details for numerical modeling of the feed region and the equivalent source. Note that the computed patterns do not have the case of -60º scan as OSU did not provide data for this scan angle. Also, the computed patterns cover only a half space, -90º to +90º, which is an inherent limitation of the infinite array model. On the other hand, the measured data show -60º-scan and cover the full 360º appropriate for a finite array. (In practice, a planar array panel needs to exhibit full 360º patterns to show that it has no disruptive back when integrated to the system or installed on a platform.) As can be seen, the agreements between computed and measured gain patterns are fairly good.

The measured and calculated antenna gain data over 2-12 GHz scan angles of 0º, 30º, 45º, and 60º are shown in Fig. 9 and Fig. 10 for *H*-plane and *E*-plane scan, respectively. The "Maximum Array Gain" in Figs. 9 and 10 is the theoretical maximum for a large planar antenna of this size with uniform amplitude distribution and a linear phase taper appropriate for the scan angle. Since in principle the array antenna's gain at the scan angle of 0º should be identical between *H*-plane and *E*-plane, their small differences arose from the errors in the anechoic chamber, instrumentation, test setup, and operator.

As can be seen, the agreements between computed and measured gain patterns are fairly good except for frequencies below 2.7 GHz and above 11.4 GHz where the range antenna, power dividers, and TTD lines, are deficient. The gain data displayed were the measured gain compensated with "BSN Loss" which is the loss of the TTD BSN for a particular scan angle, plane of scan, and frequency. "BSN Loss" is estimated by adding the path losses of all sections of the BSN. To determine BSN Loss by measurement, one could directly measure the path loss for each terminal, with the other 255 of the 256 output terminals (to array elements) terminated in 50 ohms. For high accuracy this has to be done for each of the 256 terminals and for each scan angle. We did not do it this way because it would be too costly and time consuming for the present effort; this would introduce some errors of course.

That the measured patterns are close to, and sometimes better than, the simulated performance can be partially attributed to TWAA's robust performance, which had been revealed in a simulation study of manufacturing tolerance on array active impedance conducted earlier.

The measurements were conducted and data recorded and examined before the simulation data were obtained and provided to WEO by OSU. As this was believed to be the first full-fledged characterization in the controversial field of MPPA—except for those of flared notch type—the tests began with some sense of uncertainties and apprehension. It was a relief when the first measured patterns looked like ideal theoretical patterns based on classical array theory. But it was after having received and processed the corresponding

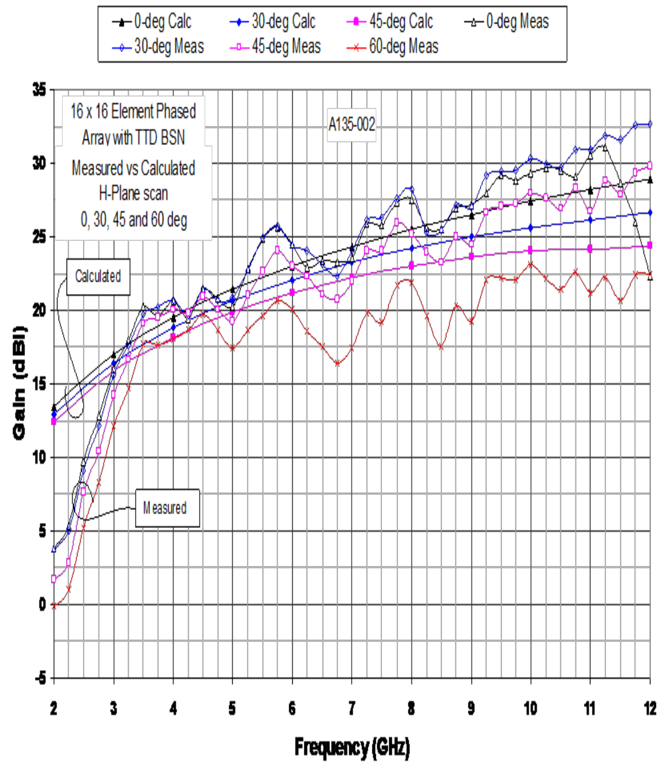

Fig. 9. Comparison of measured and simulated *H*-plane antenna gain over 2-12 GHz for scans at 0°, -30°, -45° and -60° off broadside.

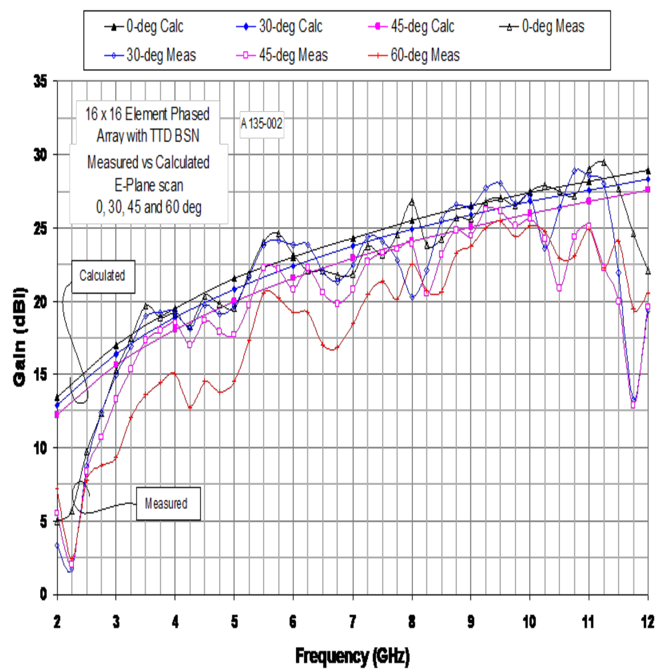

Fig. 10. Comparison of measured and simulated *E*-plane antenna gain over 2-12 GHz for scans at 0°, -30°, -45° and -60° off broadside.

calculated gain pattern data from OSU for *H*-plane and *E*-plane scans that finally completed the characterization of TWAA with confidence.

There are no calculated data for X-pol from OSU. Random sampling of X-pol showed that they are between -20 to -30. After the surprising X-pol problem for MPPA was brought up in [6], a systematic measurement on X-pol of TWAA was *started, and is still ongoing. So far the performance of -20dB> X-pol > -30dB still holds satisfactorily for the TWAA.*

V. Discussions and Conclusions

A. Computational Difficulties and Limitations

OSU has not yet explained as to why simulation data for the case of ±60º were not provided. WEO speculates that OSU was not satisfied with the data due to failing some numerical test criteria such as numerical convergence.

The infinite-array unit-cell analysis has inherent deficiencies arising from ignoring the edge effects in a real-world array, which is always finite. Also, in numerical analysis it is increasingly more difficult and expensive to achieve relative convergence as the main array beam is steered away from broadside.

The author also speculates that some approximations employed in the algorithms of commercial software, such as those for computing fields or equivalent currents, speed up computing but also degrade the accuracy of the numerical model. Round-off errors arising from large computations with limited CPU RAM further aggravate the problem, as discussed in [19].

At one time, computation on TWAA with finite elements for the 256-element array was explored by OSU. But the computational effort was highly burdensome, even for one single row or column of the array, and thus OSU abandoned this approach and took this author's suggestion of using the unit-cell approach.

B. MPPA's Bandwidth Limitations for Efficient Scan to 60º and X-pol<-10dB

Earlier, under Section II Item.1, we made a bird's-eye review on the bandwidth limitation of MPPAs for efficient scan to 60º and X-pol<-10dB as suggested by [6]. From there one can see that [6] revealed an extremely important problem in MPPA design that is not well known, at least to this author: *cross-polarization (X-pol) is actually the most serious limitation for MPPAs, and it is so difficult to solve that "tricks" are needed even for a rather lenient specification of X-pol<-10dB.* According to [6], this limitation is faced by all existing efficient wide-scan MPPAs, including Vivaldi, stacked patch, connected arrays, TCA, or TCDA, etc.

The "scan to 60º" KPP is the next most demanding goal for MPPAs. However, as discussed earlier, this author suggests that, *for most applications, scan to ±55° scan is adequate and can be accepted as a realistic goal*.

Indeed, this author foresaw that, in MPPA design, to achieve a good radiation pattern is more difficult than impedance matching, as discussed in the following excerpts from an unpublished paper that had previously been submitted to the 2015 IEEE MTT Symposium, and published later in FERMAT [20]:

"It is also worth noting that, for a large array antenna, impedance matching is a much simpler engineering problem than optimizing radiation patterns. Failures in radiation patterns can be very difficult and expensive to fix—due to the large number of parameters and dimensions involved in optimizing pattern performance over multioctave bandwidths. Mathematically speaking, for a planar phased array, impedance matching per se can be formulated as a simple scalar Fourier transform of scalar parameters; yet the radiation pattern is a vector Fourier transform of vectors and tensors. For the latter problem, analysis is already a very difficult problem very cumbersome to manipulate, not to say synthesis over multioctave bandwidths and large scan angles."

This author would like to point out that he has not yet seen any valid theoretical findings that can set MPPA's bandwidth limitations for efficient Scan to 60º and X-pol<-10dB. From a practical point of view, a multioctave bandwidth over, say, >6:1 may not be an optimum design goal because of the high cost and complexity associated with it, even though microwave components generally strive for continuous coverage over 2-18 GHz as an accepted standard since early 1960s.

It is worth pointing out that for non-TWAA approaches, Wheeler's visionary CSA concept [10] is both beneficial and burdensome. In using the waveguide concept to analyze an infinite array, one must recognize that waveguides are not broadband, thus difficult to be impedance-match for broad bandwidth. Consequently, [6] concluded that they worked on the Wheeler concept for thirteen years to understand them and solve feeding mechanism—with rather limited bandwidth. In this regard this author had discussed the feeding issue in [4]-[5], which foretell some of the pitfalls in applying Wheeler's CSA concept.

Indeed, the feeding problem for an antenna is not only difficult for hardware design, it is also difficult in analyses of antennas and arrays [19]. As a result, the feed issue is generally avoided in theoretical works. In systems integration, there are frequent disputes on whether a system's performance deficiency is due to the antenna or its feed. Therefore, the method of characterization for MPPA as presented in this paper also aimed at obtaining the fundamental performance data in a clean-cut, though clumsy, manner.

C. TWAA's Bandwidth for Efficient Scan to 60º and X-pol<-10dB

The measured data presented here are those for the second of the three models. The data indicate that the TWAA has a 2-12 GHz (6:1) bandwidth if not for the low gain at frequencies below 2.7 GHz and above 11.4 GHz. We suspect that the lower measured gain at frequencies below 2.7 GHz is due to the poor patterns of the range antenna, which is a small 2-12 GHz horn, and the 2-18 GHz power dividers; and that the low gain at frequencies above 11.4 GHz is due to phase errors of the TTD lines that increases with increasing frequency.

Indeed, in the ongoing tests on the third model, greatly improved performance so far enables this author to state that, by the standard of TRL-6, the TWAA should be able to achieve a 2-12 GHz (6:1) bandwidth that meet the KPPs specified in [6].

It is worth commenting that the present TWAA design is by no means optimized. There are plenty of rooms for further enhancements of its bandwidth under various requirements for performance and systems integration, etc. Also, since systems integration is a major hurdle that needs to be overcome, by today's trend set by the globalized market place and voiced by commercial and government users, TWAA is at a stage ready for integration to the system.

Nevertheless, we are in the process of refining the accuracies of the measurements and the BSN to characterize the TWAA more precisely. We are also actively seeking an independent laboratory to perform some validation or qualification tests.

ACKNOWLEDGMENT

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