Traveling-Wave Antenna (TWA) Array as a Thin Multioctave Planar Phased Array (MPPA)

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***Abstract*— Multioctave Planar Phased Arrays (MPPA) have advanced rapidly since 2000. Today, MPPA technology and its market needs appear to be nearing a point of convergence. This paper reviews the history of *thin* MPPAs, which exclude the Vivaldi antenna type, and presents modern planar Traveling-Wave Antenna (TWA) array as a thin MPPA. The differentiating features of modern planar TWA array from other thin MPPAs, and its potential high performance and other advantages, are discussed. Certain controversies in the theory and measurement of MPPAs are also reviewed and clarified. A planar TWA array design, with SEG breadboard demonstration, is presented to show potential performance of low VSWR, high-efficiency (low loss), scan angle ≤60° off broadside, over a 6:1 bandwidth and beyond.**

Keywords—array, planar array, conformal array, beamsteering, multioctave, wide angle scan; ultrawideband antenna array.

I. Introduction

Phased arrays, especially those fielded, are highly complex and costly. To reduce cost and complexity in fabrication, installation, transport, and maintenance, phased arrays have been, and will continue to be, mostly planar or quasi-planar (locally planar) in shape. Since their costs and technical difficulties increase exponentially with bandwidth and scan angle, phased arrays are mostly narrowband, typically less than 10% in bandwidth, and ≤45° in scan angle off broadside. Consequently, Multioctave Planar Phased Arrays (MPPA) having multioctave bandwidth, in particular thin MPPAs, are still largely in various R&D stages and have some controversies and ambiguities.

This paper reviews briefly the history and the state of the art of thin MPPAs, and presents planar Traveling-Wave Antenna (TWA) arrays [1]. The differentiating features and advantages of the modern *thin* planar TWA array, as well as its potential performance, are discussed. Certain controversies and ambiguities in the theory and measurement of MPPAs are also discussed and clarified.

II. Thin Multioctave Planar Phased Array (MPPA) —Its Development History

The first embryonic MPPA was conceived by Booker in 1946 [2]. Hardware development for MPPA started in the late 1980s by employing multioctave tapered horns (such as the Vivaldi antenna) as array elements. Since the tapered horn must be electrically long, these MPPAs are thick, generally $>0.25\lambda_L$, where λ_L denotes the wavelength at its lowest operating frequency [3]; they are not included in this paper. This paper addresses only *thin* MPPAs.

Booker's infinite planar array concept has many fundamental deficiencies; most importantly it has no conducting ground plane (GP), thus has the deadly problems of bidirectional radiation and EMC/EMI. In 1965, Wheeler added the needed GP to form the Current Sheet Antenna (CSA) array [4]. The CSA showed potential for wide-angle scan, though without multioctave bandwidth. Nevertheless, CSA has been credited by most researchers in thin MPPA as their basic approach. There were other embryonic MPPA concepts over the past seventy years. In particular, the planar Traveling-Wave Antenna (TWA) array described in the definitive book of Walter [1] is the origin of the modern multioctave planar TWA array to be discussed in this paper.

Due to their severe limitations, all embryonic thin MPPAs remained dormant until the advent of the multioctave planar FSS (Frequency Selective Surface), developed for scattering/radome applications, under the huge Stealth and Star Wars Initiatives from mid-1970 to 2008. In late 1990s, researchers led by Munk at the ElectroScience Laboratory (ESL) of The Ohio State University (OSU) developed multioctave planar FSS for radome application.

One type of OSU FSS in the form of an array of loaded dipole was readily recognized as the first larval MPPA [5], *yet still handicapped by the lack of a GP*. By the efforts of engineers at Harris Corporation, helped by Munk at OSU ESL, a GP was added to this FSS of dipoles, which was soon metamorphosed to *the first adult MPPA* [5]-[8]. Several other MPPAs also followed, notably those at Raytheon, e.g. [9]. Generally, they all claim to have followed Wheeler's CSA approach.

Today, complete and detailed discussions on thin MPPAs are still scanty, and some have remained ambiguous or controversial. Nevertheless, thin MPPA technology and its market needs appear to be nearing a point of convergence.

III. Planar Traveling-Wave Antenna (TWA) Array

The thin multioctave planar TWA array conceived by this author in 2007 [10]-[11] stemmed from a transmit antenna

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perspective inherent in the embryonic planar TWA of Walter [1], which is different from those of Booker and Munk that had originated from a scattering concept. However, the author's thin planar TWA array was also influenced by the scattering theory and FSS, including his own [12], as well as sampling theory in spatial domain and antenna theory based on discrete Fourier transform and plane wave spectrum for planar antennas [13]—though only as secondary proofs—and, as a result, has mutated away from the continuous-source TWA of Walter.

Since its inception in early 2007, the planar TWA array technology has been gaining maturity and recognition in both the technical field and the IP (Intellectual property) landscape of MPPA, as reflected by [14]-[17] and [10], respectively, among others. A glimpse of a recent TWA array is shown in Fig. 1, in top and cross-sectional A-A' views.

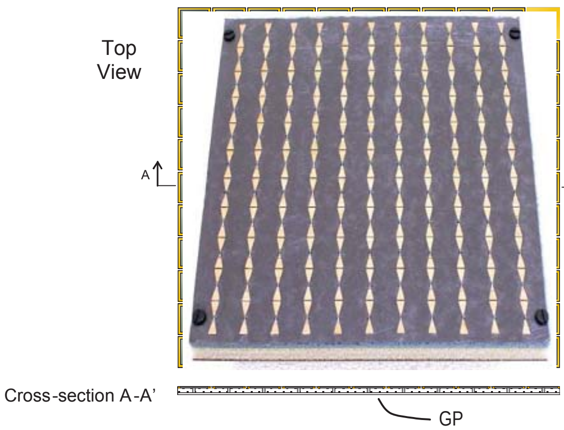


Fig. 1. Top and cross-sectional view of a planar TWA array.

This breadboard model was developed in a joint research with OSU-ESL [17]. The array elements are planar bowtie dipoles, somewhat similar to that reported by OSU in [18], which are a broadband planar traveling-wave (TW) antenna element according to [10]. As shown in the cross-sectional view, there is no dielectric substrate or superstrate, yet there is a conducting ground plane.

Although this model has a linear polarization dictated by the planar bowtie element, it readily lends itself to dual polarization and circular polarization by adding identical array elements perpendicular to existing ones. If the angular span of the bowtie elements is 90° for linear polarization, or 45° for dual-polarization, the planar array is a self-complementary structure, which would have the potential of the largest bandwidth, as had been discussed in [10] and [11], consistent with the theory of planar TWA array.

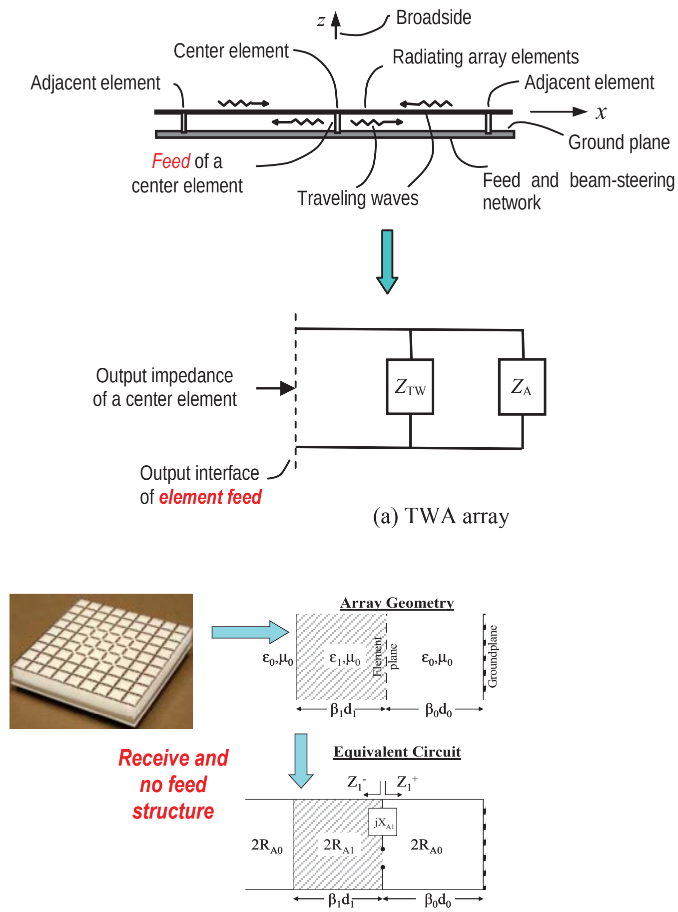
A main difference between this model and that of [18] is the latter's insertion of a resistive FSS (a high-loss substrate in a way) and a dielectric superstrate, which enables it to expand its bandwidth to 21:1 at the price of degraded performance of VSWR≤3, having one or more frequency gaps, and without scan. As revealed in [10], substrate and superstrate of dielectric or magneto-dielectric property, or metamaterial, are not necessary in planar TWA array, though their incorporation can be beneficial in certain applications. Further discussions will be presented later.

IV. Differentiation of Planar TWA Array from Other Thin MPPAs

Key differentiating features of modern TWA arrays from other thin MPPAs are as follows.

A. *Antenna/transmit Perspective of TWA Array versus Scatterer/Receive Perspective of Others*

A fundamental difference in physical concept between planar TWA array and other MPPA is that the former is based on an antenna/transmit perspective while the latter is rooted in a scatterer/receive perspective. Fig. 2 illustrates a comparison of the equivalent circuits at a center element between a planar TWA array and other typical MPPA.



(b) Other typical MPPA

Fig. 2. Comparison of equivalent circuits for a center array element: (a) planar TWA array, (b) other typical MPPA.

Note that the TWA array is for transmit and has a specific feed structure (a traveling-wave (TW) structure represented by impedance Z_{TW}) and element antenna impedance Z_A in the array environment. On the other hand, other MPPA is generally formulated in receive mode and addresses its structural feed in vague general terms without details. The TW structure in the feed region facilitates broadening of both bandwidth and scan angle of the array in a simple and efficient manner.

It is worth commenting that, first, the principle of reciprocity should hold in either case, transmit or receive, unless the array has nonreciprocal components or medium. Second, in analysis, the longitudinal component of the feed structure presents a singularity in array formulation, which is very difficult to deal with, thus routinely ignored in computation, resulting in deterioration of numerical accuracy.

This propensity of receive–only approach for other MPPAs, driven by the high cost of ultrawideband phased arrays and sometimes motivated by expediency, has built up a conviction that Scan Element Gain (SEG) is significantly different between the transmit case and the receive case and thus SEG "should be measured with the array in the receive mode," as indicated in Hansen's recent book [19, pp. 225-233], which has been commented on by this author [15].

Indeed, the scattering approach, especially the classical antenna scattering matrix and minimum-scattering antennas [20], has several fundamental limitations when applied to antennas. Its pitfalls were epitomized by the misguided and costly application to the design of reflectarrays as critiqued by this author decades ago [21].

Hansen commented that Munk's CSA approach stemming from FSS theory "is the wrong physics" (pp. 466-474 of [19]); his observation might have also come, correctly, from this perspective.

B. Coupling between Adjacent Elements

Hansen's comment above also appears to suggest that he saw an issue with Munk's coupling technique between array elements, since his recent book only accepted arrays with directly connected elements [19]. Although Munk's expansive narrative on the capacitive coupling was somewhat defective, yet its physics has a credible basis in light of the findings of Hannan et al in 1965 [22], which showed significant improvement in wide-angle scan by using lossless connecting circuits between adjacent array elements, and in particular by capacitive coupling. In this context, the TW structure in the present TWA array is a more practical and versatile technique to materialize this initial concept of Hannan et al.

The theory of planar TWA array formulates the feed region, between the radiating aperture and the conducting GP, with an expansion of TWs, which propagate parallel to the GP—in other words, perpendicular to the *Z* axis (see Fig. 2 (a)). On the other hand, Munk's CSA and other MPPA deal with this region with plane wave spectrum propagating at angles close to the *Z* axis, generally ≤60° (see Fig. 2 (b)), which has a much lower rate of convergence, to say the least, especially in dealing with the coupling between array elements.

C. The Role of Substrates/Superstrates and Metamaterial

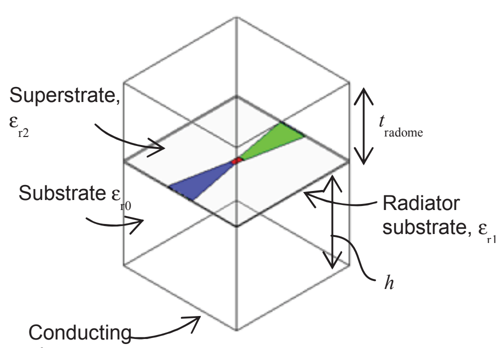
Substrates/superstrates and metamaterial play secondary roles in TWA arrays, yet are necessary elements in other MPPAs, as evidenced by their patent claims. This basic difference is actually rooted in the difference discussed under Subsection IV-A." ***Unfortunately, this fundamental difference in approaches has led to increased thickness, weight, and cost, as well as performance limitations, for many other MPPAs***.

V. Performance of a Recent Planar TWA Array

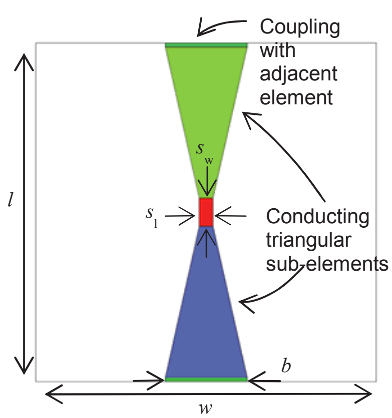
This section discusses design study of a recent planar TWA array introduced earlier as Fig. 1 in Section III and reported in [17]. The preliminary design was achieved by iterative optimization via computer simulation using a commercial software, carried out at OSU ESL under Dr. John Volakis. Final designs for a finite array were then generated at WEO. To verify their theoretical performance, several breadboard models based on the Scan Element Gain (SEG) technique were designed, fabricated and tested. The process, results and their interpretation are discussed as follows.

A. Preliminary Design by Computer Simulation

As discussed, the array element of the breadboard model is somewhat similar to that in [18]. The present design goals are: linear polarization, low VSWR, high-efficiency (low loss), wide scan angle of ≤60° off broadside, over a multioctave bandwidth. It is worth pointing out that the full array design is within the confines of [10]—for IP protection. The numerical model is an infinite array with periodic unit-cell configuration with minimal feed structure, as shown in Fig. 3.



(a) perspective view



(b) exploded top view

Fig. 3. Unit cell of planar TWA array with planar bowtie elements: (a) perspective and (b) exploded top views.

In the unit cell, the length l and width w must be smaller than $\lambda_h/2$, where λ_h is the free-space wavelength at the highest operating frequency, in order to suppress grating lobes. The radiator in each array unit cell is a broadband element of two triangular conducting sub-elements (in other words, a planar bowtie dipole) on a substrate with relative permittivity ε_{r1} and thickness h. The radiator is closely spaced over a ground plane, with a superstrate layer above the radiating element as a radome. A simple structural feed region is assumed.

The physical parameters of the array are adjusted to achieve an optimal performance. Because of the large quantity of physical parameters and high volume of performance parameters (due to multioctave bandwidth and wide range of scan angles), the optimization process has been guided by judicious engineering judgment with tenacious efforts.

The results of computed Smith chart and VSWR data of the infinite-array simulation for an optimized design are shown in Fig. 4, which are fairly good at this stage of the research. As can be seen, the VSWR over 0°-60° scan angles is < 3:1 from f_l to $6f_l$, over a 6:1 bandwidth. Therefore, there is still considerable room for further optimization of the design.

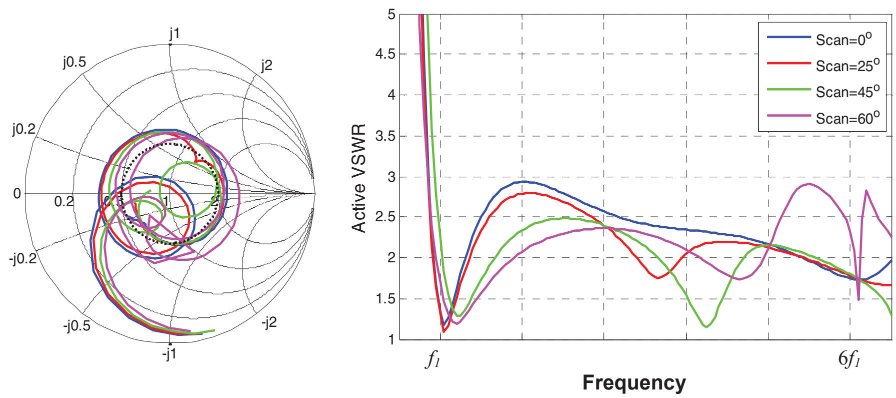


Fig. 4. Computed Smith chart and VSWR data showing 6:1 bandwidth.

B. Design and Empirical Study by SEG Technique

Computer simulation and optimization as discussed in the preceding subsection led to a planar TWA array design meeting the general design goals. The next step was to design and layout a physical array that has a feed network and use real-world hardware. Specifically, the layout of the bowtie sub-elements and the capacitive coupling between bowtie elements benefitted from the techniques partially disclosed in [23]-[26]. The multioctave balun feed was based on a proprietary technology developed at WEO over many years for TWAs [28].

As is the usual practice, the Scan Element Gain (SEG) technique was employed first to test the design [15] since it is very expensive to fabricate a full-fledged MPPA, even a small one. SEG is essentially the widely used empirical "Active Element Pattern" (AEP) technique discussed recently in [15], which tried to resolve and reconcile recent inconsistencies and controversies brought up by Hansen [19], [29]. We will later clarify the inconsistencies and controversies again.

Several 11×11-element passive SEG planar arrays with small variations were fabricated, including one that was essentially the same as that in Fig. 3, which was fabricated and tested to verify that the changes in the design have only small effects on the electrical performance. However, *the SEG model presented here in the following is different from that in Fig. 3*. Its top and cross-sectional views have been shown in Fig. 1, its back view is shown in Fig. 5. The passive SEG array has only its center element excited, for either transmit or receive, and has no active or nonlinear component or material.

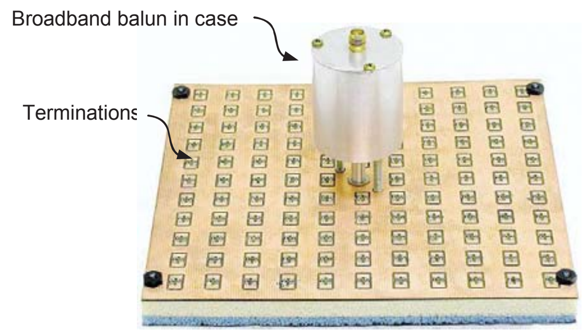


Fig. 5. Back view of an SEG model showing balun feed for center element and resistive terminations for each array element.

Note that on the metallic conducting surface there are terminating resistive loads of 100Ω, which are connected to the array elements via coaxial cables, and that they match the broadside radiating resistance of the array element, which are approximately 100Ω. The metallic cylinder in the photo contains a broadband balun connected with the center element of the array and an output connector compatible with standard female SMA connector.

The planar TWA array is designed to be impedance matched also in the feed region, between the layer of radiating layer and the ground plane, to facilitate the propagation and radiation of the desired TW ***without the use of any dissipative material or components, nor substrate or superstrate*** (except for a thin dielectric substrate that supports the mechanical structure of the array elements and their inter-element coupling mechanism).

Note that a major difference between the planar TWA array and other MPPAs is that other MPPAs rely critically on the use of dielectric superstrates and substrates, and often also on a backing sheet with dissipative property or of a metamaterial with certain desired impedance; none of which are necessary in the TWA array design.

Fig. 6 displays measured VSWR over f_l to $9f_l$, a 9:1 frequency bandwidth, for the case of broadside scan. As can be seen, there is fairly good impedance match over $1.6\,f_l$ to $9f_l$, a 5.6:1 bandwidth shifted slightly upward from the original design goal. The discrepancies between the measured and computed data were later found to be mainly due to (1) the phase/amplitude imbalances in the feed balun of the center array element, (2) the simplistic modeling of the feed region due to the limitations of the software.

It is worth noting that, although planar phased arrays are a key communications technology that can provide seamless, robust connectivity, this technology is handicapped by poor performance, large size, and high cost of feed network, electric or optical, needed for beam forming, especially for the case of transmit. For example, a recent plenary paper by Dr. Eli Brookner of Raytheon [30] revealed that “Raytheon has demonstrated a notch radiating element that is capable of going from 1.8 to 18 GHz, a 10:1 bandwidth [5, 79]. It can be dual polarized and scanned to 60° [5, 79]. In an array it would have a 3:1 bandwidth because of the baluns behind it.” The author would like to add that this problem is more than 15 years old in the array community [24]-[25], and he believes that today it should be much easier to resolve.

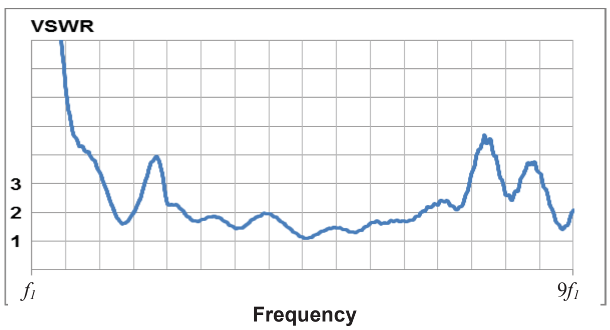


Fig. 6. Measured VSWR for the case of broadside scan.

Fig. 7 shows measured SEG patterns over f_1 to $9f_1$. Their broad patterns indicate potential for wide-angle scan performance, even near f_1 where VSWR is poor (see Fig. 6). Fig. 8 shows measured peak gain per element of this SEG array versus the theoretical maximum gain, showing good efficiency. The overly high gain at some frequencies is due to errors in the measurement system and the finite size of the array. The broadband SEG data in Figs. 6-8 are also fairly consistent with each other.

The measured results agree fairly well with computed gain pattern and impedance for maximum scan of ±60°, over a 6:1 bandwidth of f_1 to $6f_1$, considering the limitations in the simulation and SEG models as well as the analysis and measurement difficulties involved in this small research effort.

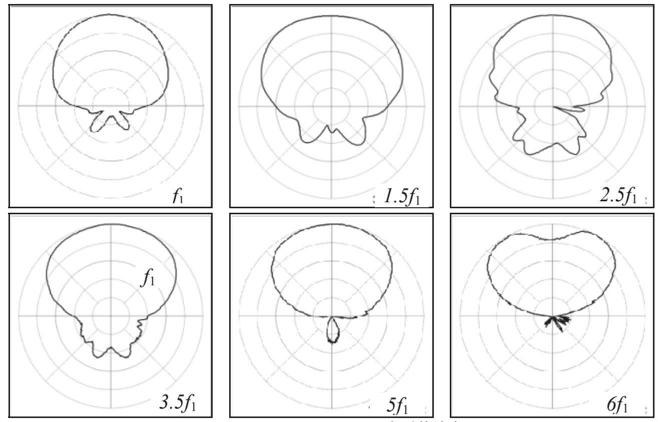


Fig. 7. Measured SEG paterns.

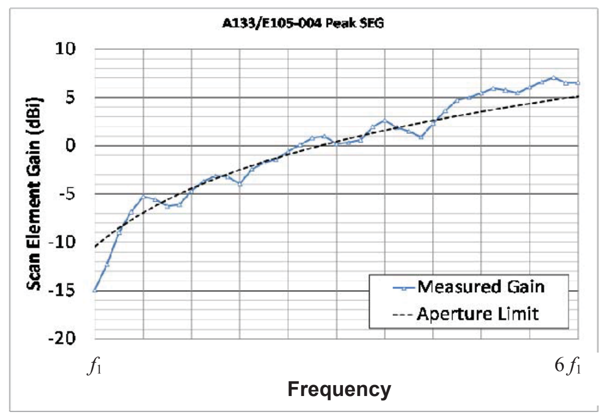


Fig. 8. Measured peak gain per element vs theoretical maximum of an SEG model.

VI. REDEFINING AND CLARIFYING SEG ARRAY

Hansen remarked in [19] and [29] that SEG (called SEP by him) is significantly different between the transmit and receive cases, that it should be measured with the array in the receive mode, and that the scan impedance cannot be measured with a network analyzer. He also indicated, correctly, that here the “pattern” really means “gain pattern” (per element), rather than the misleading IEEE definition. The author concurs and takes a further step to replace SEP by SEG and highlights his clarifications on these controversial issues as follows.

Scan Element Gain (SEG) is denoted by G_e, or $G_e(\theta, \varphi)$, and is, by definition, given by

$$G_e(\theta,\varphi) \equiv G/N \qquad (1)$$

where N is the number of elements in the planar periodic array, and G is the gain of the array.

The maximum realizable gain of a planar antenna with physical aperture A is that of uniform illumination, that is,

$$G_e \leq \eta(1-|\Gamma|^2)\,[4\pi(A/N)\cos\theta]/\lambda^2 \quad (2)$$

where η is efficiency to account for dissipative loss and Γ is the reflection coefficient. Note here that η, Γ, G_e, and the array gain G are all functions of scan angles (θ, φ) and frequency f.

The analyses of Pozar [27] and Hansen [19], [29] have two deficiencies in their formulation of the problem: (1) blanket assumption of a single mode, (2) use of scattering matrix to handle the spatial feature of array elements. In general, a phased array has more than one non-evanescent Floquet and waveguide modes. The spatial scattering matrix formulation transforms a simple antenna problem into a complex open scattering problem that is hard to connect with array parameters and test instrumentation. These two deficiencies led to the apparent inconsistencies observed by Hansen.

To circumvent these problems, this author formulates the problem as a simple yet full-fledged antenna problem, and reduces the general multi-mode problem to a single-mode problem by dictating that the array element feed network is impedance-matched at broadside scan. The basic approach was highlighted in [15].

As to Hansen's comment that the SEG measurement should be performed in the receive mode, not in the transmit mode, this author would like to suggest a possible explanation. For the receive case, the measurement is conveniently done with the center element connected to a receiver—in a straightforward antenna setting. For the transmit case, the test is not convenient and the reflection is sometimes measured by using a directional coupler in the center element—in an antenna/scattering setting—which is not the same problem as that of the SEG array since all the elements are now excited. The finite SEG array should exhibit identical characteristics, such as impedance, gain, and pattern for both transmit and receive cases, as they should according to the principle of reciprocity.

VII. Conclusions

Computer simulation and empirical breadboard study by SEG pattern technique have further advanced the feasibility of the planar TWA array as a thin MPPA. A planar TWA array design, with SEG breadboard demonstration, is presented to show performance of low VSWR, high-efficiency (low loss), scan angle $\leqslant 60°$ off broadside, over a 6:1 bandwidth. The deviations of measured data from simulation data are primarily due to the phase and amplitude errors of the balun employed in the active element, the fabrication and measurement tolerances, the limitations of the simulation software used, as well as the differences between the theoretical model and the actual array containing the feed network.

The TWA array does not use dielectric slabs, ferrites, lossy matching, or metamaterial, and is therefore thinner, more efficient, and less costly than other MPPAs. The author also clarifies several ambiguities and controversies in the theory and measurement of planar phased arrays, in particular the MPPAs.

The next step will be the design, fabrication, and testing of a full-fledged small TWA array. To demonstrate the technology, the difficulty in the expensive feed network can be circumvented by using an existing feed network, preferably one of true-time-delay (TTD) or one of limited scan angles and frequencies. The test data would shed light on many issues on the TWA array as well as the design, computer simulation, SEG technique, and small-array technique. The author also believes that today the development of full-fledged beamsteering network for good performance and low cost feasible as technology and pricing in design and manufacturing have become more favorable by 2 to 5× than those 15 years ago.

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