WIDEBAND VIVALDI ARRAYS FOR LARGE APERTURE ANTENNAS

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Single- and dual-polarized arrays of Vivaldi notch elements have been extensively analyzed by using efficient numerical analyses. From these analyses and from experimental studies, element designs and array configurations have been determined to provide more than two octaves of bandwidth while scanning to 45° from broadside in all directions. Parameter studies illustrating the effects of some key design parameters are presented. Vivaldi notch elements are linearly polarized in their principal planes and elliptically polarized in the intercardinal planes. Nonetheless, it has been shown that full polarization information about the radio source can be extracted from the signals received on orthogonal antennas. A few issues related to fabrication and assembly of dual-polarized arrays are discussed.

1 Introduction

Phased array antennas are attractive for applications that require rapid scanning of the beam or multiple simultaneous beams. Recent and anticipated improvements in digital receivers and signal processing make phased arrays especially attractive for wideband searches of large sectors. A properly designed array can provide a very large number of simultaneous beams for signals of various frequencies and bandwidths, limited primarily by digital processing capabilities. To accomplish this, the receiving aperture is comprised of elements that exhibit good impedance match and wide radiation patterns over the entire band of operation. Furthermore, these characteristics are maintained in the presence of coupling to neighboring elements. At the present time, the Vivaldi notch element is the only candidate that fulfils these requirements and can be positioned closely enough in the array to avoid grating lobes over two or more octaves of bandwidth.

The use of endfire tapered slot antennas for wideband/wide-scan phased arrays was proposed more than two decades ago [1]. A number of successful arrays have been demonstrated [2]-[6], but these antennas have not realized their potential for wideband operation due, in part, to difficulties in developing fully functional designs. Although the advent of accurate numerical simulations for these antennas has made it possible to replace many of the empirical iterations with numerical analyses, the fundamental operation of these antennas is not yet well understood, nor can designers reliably create new arrays fulfilling specified requirements without a great deal of design iteration. Rapid convergence to a good design is still highly dependent upon the experience of the designer and few results have been published to aid designers in choosing starting points or in the most fruitful areas to explore when a design needs improvement. The intent of this paper is to present a summary of some key characteristics that relate to successful designs. Through extensive numerical studies, some of the important design parameters are beginning to be understood and insights are being developed into what is needed for a successful design and how to improve a design that is nearly good enough.

A.B. Smolders and M.P. van Haarlem (eds.)
Perspectives on Radio Astronomy – Technologies for Large Antenna Arrays
Netherlands Foundation for Research in Astronomy - 1999

2 Element Configurations

Endfire tapered slot antennas have been built in a variety of configurations. As originally proposed [1], the antenna is formed from two copper-clad substrates bonded together with a stripline conductor in the middle and ground planes having flared slots on the outer surfaces. The flared slotlines couple to the stripline through a transition and radiate off the ends of the substrates. Several variations of the original design have been explored [7]-[11]. Four variations are depicted in Fig. 1. The stripline and balanced antipodal structures display a symmetry that, theoretically, leads to perfect linear polarization in the principal planes. In practice, careful fabrication of these antennas leads to very low cross-polarization (20-30 dB below the peak copolarization) in the principal planes. However, all endfire tapered slot antennas display high levels of cross-polarization in the diagonal planes. Fig. 2 indicates the axial ratio that is typically observed as a function of scan. The figure depicts one quadrant of u-v space where the principal planes are the axes. The axial ratio deteriorates fastest for scanning in the diagonal plane. In the diagonal plane, it is common for the axial ratio to decrease to approximately 10 dB at the angle for which the copolarized response has decreased to –3 dB relative to broadside.

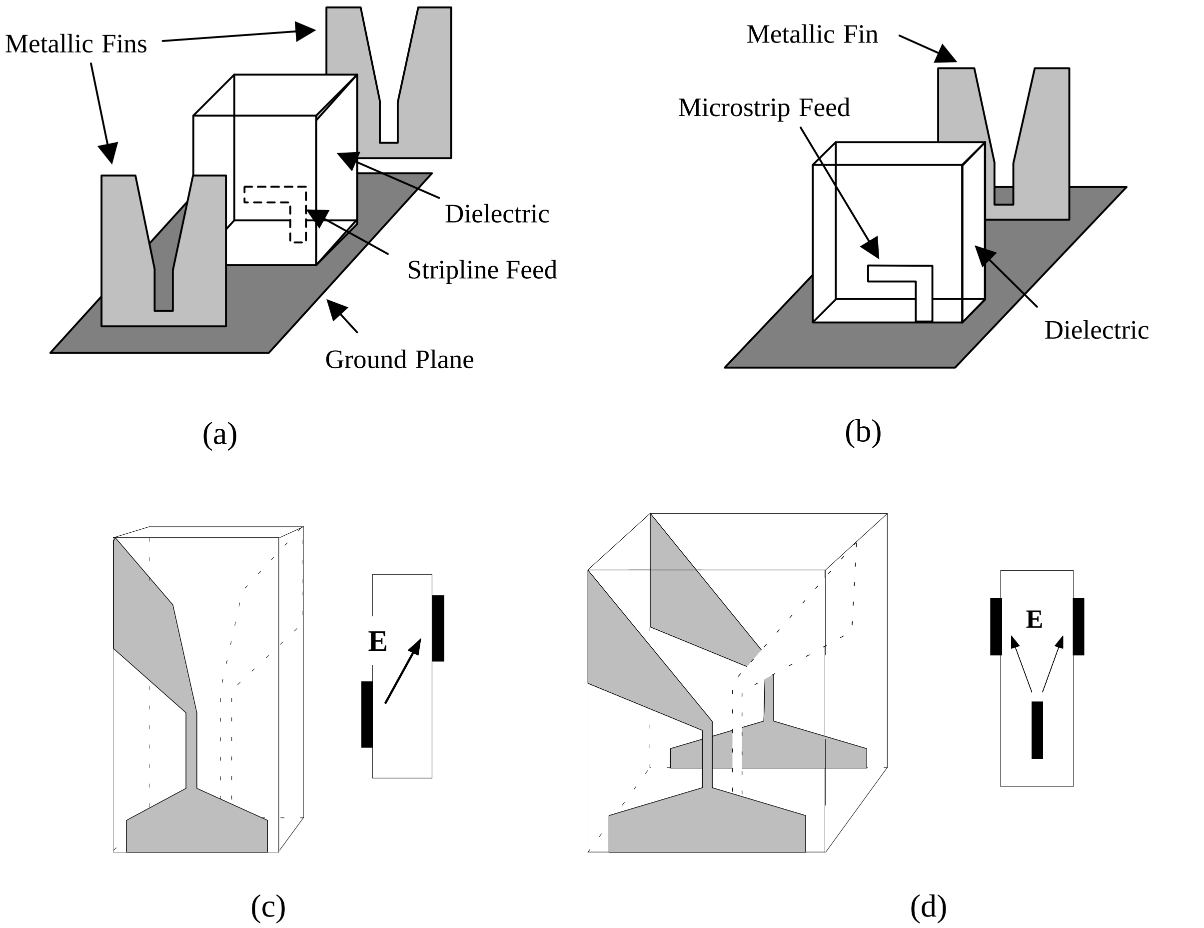
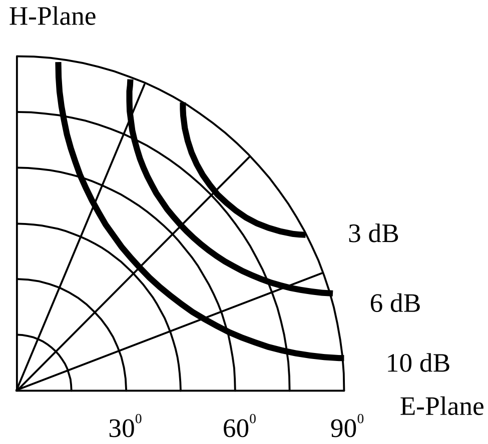


Figure 1. Some variations of the original tapered slot antenna configuration. (a) stripline version consisting of two ground planes and one stripline feed, (b) microstrip versions consisting of one substrate with a ground plane on one side and a microstrip conductor on the other, (c) antipodal antennas consisting of a gradual transition from microstripline to antipodal strips and then to antipodal flared radiators, and (d) balanced antipodal antennas that utilize stripline feed and a second ground plane with tapered metalization.

One of the key characteristics of endfire tapered slot antennas is their ability to operate over very wide bandwidths. When the antennas are electrically large (longer than 3 or 4 o and aperture heights greater than 0.5 o) they operate in a wide-band quasi-traveling-wave mode that has a moderately high gain beam (beamwidths from 30° to 90° are typical) with first sidelobe at -10 to -13 dB. These antennas have been used for spatial power combiners and limited scan applications [12]. However, they are not useful for wide scan phased arrays because the elements are too large to fit into the required array spacing. When the antennas are used in a wide-band phased array they must be smaller than 0.5 wavelength at the highest operating frequency, which makes them very small at the lowest operating frequency. In this case, an individual element will have the wide beamwidth needed for wide scanning. Although antennas that are very small do not usually radiate well as single elements, in an array they can be made to operate with SWR < 2 when the element aperture size is less than 0.1 λ_o x 0.1 λ_o.

Figure 2. Typical axial ratio contours plotted on u-v scan plane coordinates. antennas are linearly polarized in principal planes.



3 Arrays for Wide Bandwidth and Wide Scanning

Until recently, the computational requirements for accurate analysis of wideband Vivaldi arrays were too great to permit extensive parameter studies of these antennas. Now, however, the availability of powerful computers and efficient algorithms makes it possible to evaluate proposed designs prior to building prototypes and to optimize performance by varying key parameters. Furthermore, modern analyses can predict anomalies that limit array performance so that they may be avoided by careful modification of the antenna design. The results presented below were obtained by using full-wave method of moments analyses [13]-[15]. These analyses are based on the periodic nature of infinite arrays. The results are a good approximation to those of most elements in a large array. As is well known, for infinite arrays, the input reflection coefficient, $\Gamma(\theta,\phi)$, of an element is directly related to its radiation pattern, $F(\theta,\phi)$,

$$F(\theta,\phi) = [1 - |\Gamma(\theta,\phi)|^2] \cos\theta.$$

Accordingly, reflection coefficient and element pattern are alternative (and equivalent) descriptors of the performance of a large phased array antenna. Several key design parameters for Vivaldi notch arrays are indicated in Fig. 3 and 4.

Feed Transition: Important parameters of the feed transition include the widths of the stripline and slotline, and the sizes of the stripline stub and the slotline cavity. To date, little work has been done to explore the impact of the dielectric thickness and permittivity. All of the results presented here are for a commonly used dielectric with $\varepsilon_r = 2.2$. It has been shown [16] that various combinations of substrate thickness, stripline width and slotline width yield reasonably good results, i.e., bandwidths greater than 4:1. However, most of the parameter studies performed to date have used a limited range of these parameters.

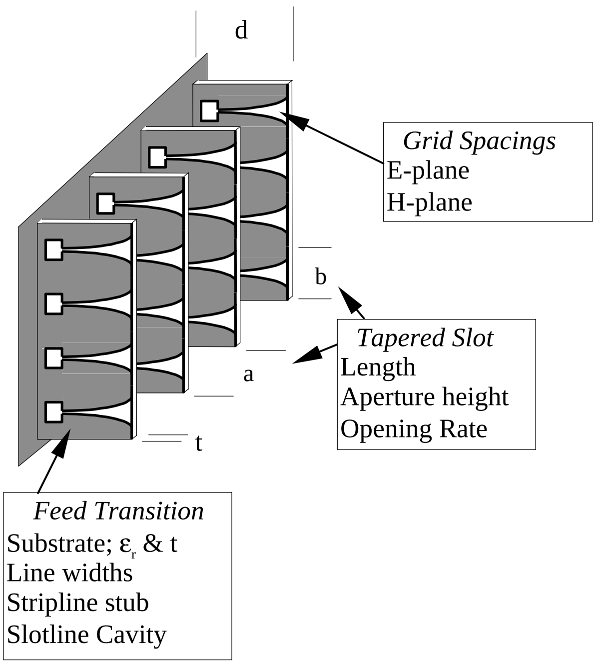


Figure 3. Key design parameters of single-polarized array.

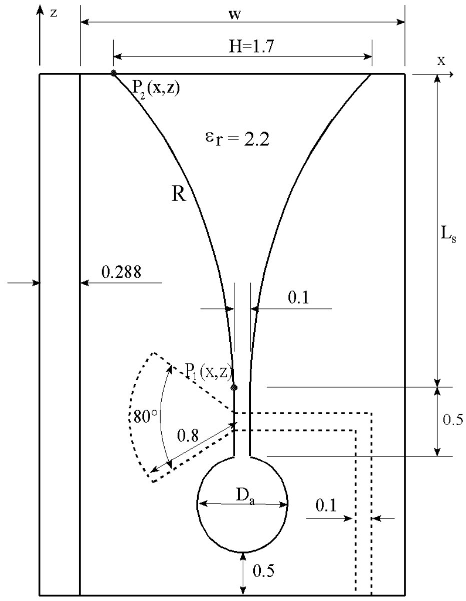


Figure 4. Key design parameters of notch antenna element. Dimension in cm.

The stripline stub has been shown to create a series reactance that is independent of scan angle and of the other key design parameters [16]. This series reactance combines with the scan-dependent antenna impedance to produce the total input impedance of the array element. The slotline cavity, however, has an important impact on the array's performance. The cavity affects the scan-dependent impedance of the antenna and also interacts strongly with other design parameters. These effects are indicated in one of the figures below.

Tapered Slotline: The best results for wideband scanning arrays have been obtained by using exponentially flared slotlines. The flare is described by

$$x = c_1 e^{Rz} + c_2 \tag{1}$$

where

$$c_1 = \frac{x_2 - x_1}{e^{Rz_2} - e^{Rz_1}} \tag{2}$$

$$c_2 = \frac{x_1 e^{Rz_2} - x_2 e^{Rz_1}}{e^{Rz_2} - e^{Rz_1}} \tag{3}$$

The points (x_1, z_1) and (x_2, z_2) are the end points of the flare and R is a parameter that is varied to control the shape of the slot. The aperture height, H, must not exceed the E-plane grid spacing, which should be less than one-half wavelength at the highest frequency if grating lobes are to be avoided. Therefore, H can be fixed and the slot length, L_s, and opening rate, R, can be varied to optimize array performance.

Grid Spacing: The grid spacings in the E- and H-planes determine the onset of grating lobes, which limit the upper frequency of the array. Furthermore, certain impedance anomalies are related to the grid spacing, and smaller spacing frequency improves the bandwidth of the array.

Interleaving two orthogonal single polarized arrays, as shown in Fig. 5 forms dual polarized arrays. The elements should be electrically isolated at the corners of the unit cells, where the substrates cross. In Fig. 5, this is achieved by a conducting post at the corner. Failure to provide this isolation leads to resonances that adversely affect array performance.

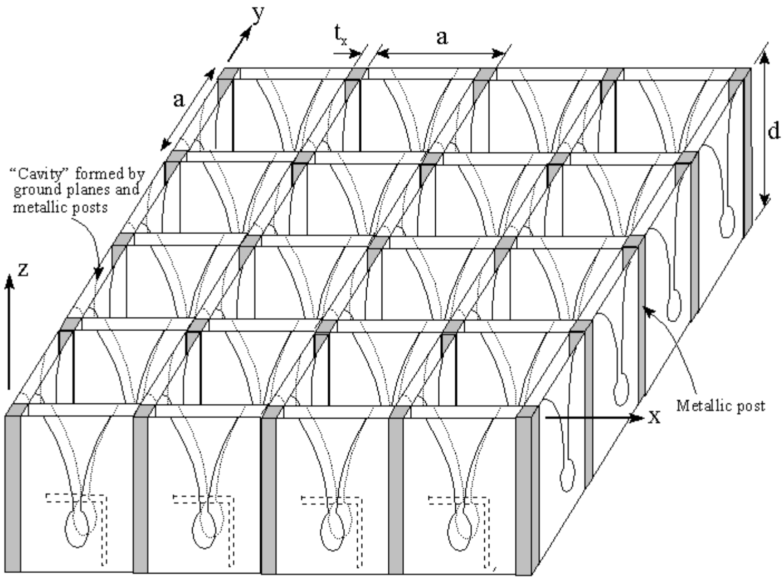


Figure 5. Dual-polarized array with conducting posts at corners of unit cells.

4 Results of Parameter Studies

Parameter studies of single-polarized arrays of tapered slot antennas [16]-[17] have yielded much insight into the effects of each design parameter on array performance. This has permitted the design of an array with predicted SWR < 2 for 5:1 bandwidth and scanning to 45° from broadside in all planes. Recent studies of dual-polarized arrays have produced similar results. This was accomplished by observing trends, such as the changes in SWR when the diameter of the circular slotline cavity or the exponential opening rate of the tapered slotline are changed.

Slotline Cavity Diameter: As the cavity diameter, D_a, increases the lowest operating frequency decreases, yielding increased bandwidth. However, increasing the size too much causes the SWR to exceed 2:1 within the operating band. These results are shown in Fig. 6. Fig. 7 shows the same effect when the array is scanned to 45° in the E- and H-planes. In the E-plane, the array performance improves as the beam scans further from broadside, whereas the performance degrades as the array scans in the H-plane. Also, the array encounters impedance anomalies in the H-plane. These manifest themselves as "spikes" in the SWR at 4.9 and 5.5 GHz in Fig. 7b. The small discontinuities that appear at lower frequencies are artifacts of the frequency interpolation scheme [18] used to reduce computation time. The true curve passes smoothly through these regions, as has been verified by detailed computations.

For scanning in intercardinal planes, the input impedance of the array elements is approximately a weighted average of the values in the E- and H-planes. That is, the impedance at a particular value of θ in the diagonal planes is approximately the average of the values at that θ in the E- and H-planes. At scan angles closer to the E-plane, the impedance resembles more closely the E-plane value, whereas at angles closer to the H-plane it resembles the H-plane value.

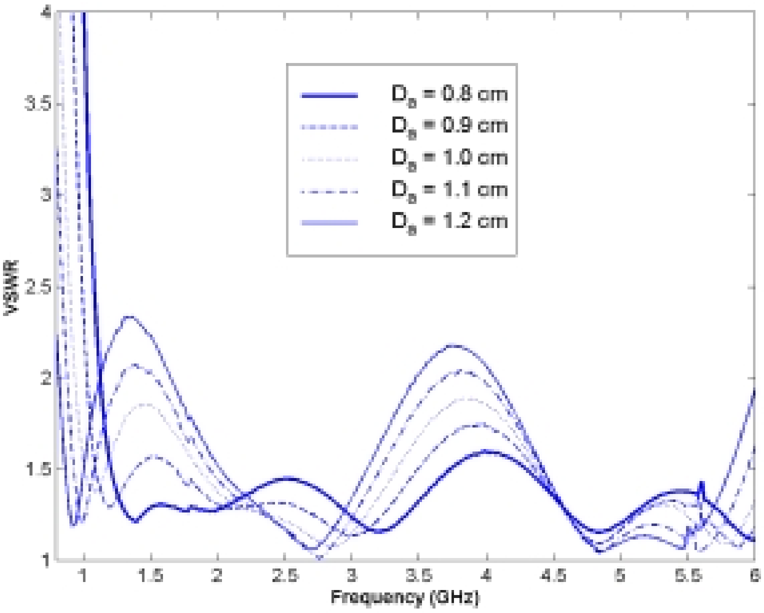
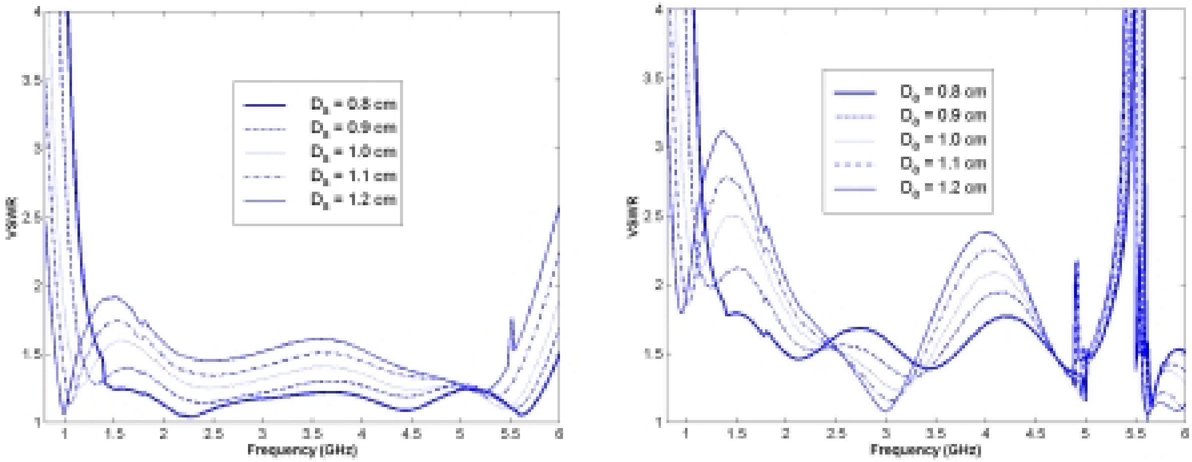


Figure 6. SWR for dual-polarized arrays with various slotline cavity diameters. Beam pointed to broadside. Element configuration as in Fig. 4; L_s = 4.5 cm, w = 2.0 cm, R = 0.3 cm^{-1}.



(a) (b)

Figure 7. Effects of slotline cavity for array scanned to (a) 45° in E-plane and (b) 45° in H-plane. Antenna parameters as in Figure 6.

Exponential Opening Rate: The effects of changing the opening rate, R, of the exponential slot flare are illustrated in Fig. 8. For the range of the parameter shown here, increasing R lowers slightly the minimum operating frequency while also increasing the first and third in-band humps of the SWR and decreasing the second. The spikes at approximately 5.5 and 5.7 GHz are anomalies that disrupt the wideband performance of the array.

5:1 Bandwidth Example: By using the results of studies such as those described above, a dual-polarized array with predicted bandwidth of almost 5:1 has been designed. The array resembles the drawing in Fig. 5 and the elements are like those depicted in Fig. 6a. The predicted SWR at three scan angles (broadside, 45° E-plane and 45° H-plane) are shown in Fig. 9. The array has SWR < 2 for all scan angles out to 45° and for all frequencies from about 1 GHz to about 5 GHz.

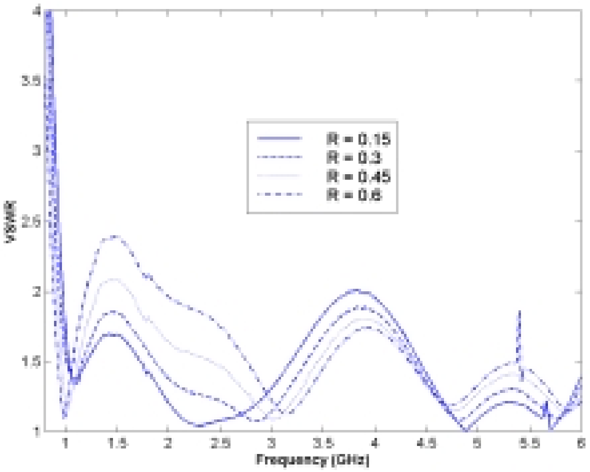


Figure 8. Effects of exponential opening rate. Antenna parameters same as Fig. 6; D_a = 1.0 cm.

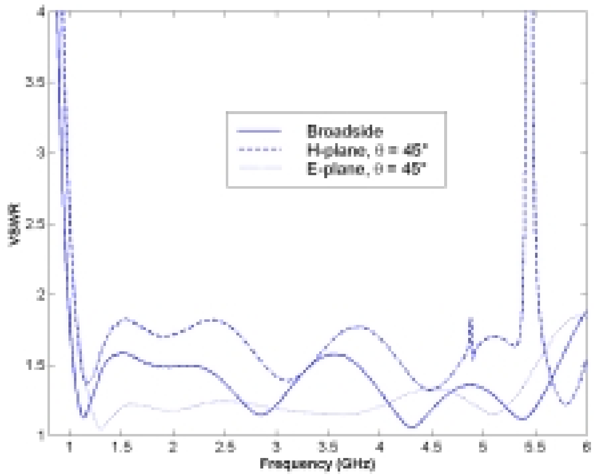


Figure 9. Predicted performance of dual-polarized array.

5 Fabrication Considerations

Vivaldi notch antenna arrays are known to exhibit bandwidth limiting resonances if the individual elements are not properly connected to neighboring elements. The metallic posts between elements in Fig. 5 isolate the fields within the dielectric substrate of the elements. This is essential to achieve good performance. Also, it is essential that every element be connected to the posts at the corners of the unit cells. Failure to maintain good electrical contact between at the junctions of unit cells can lead to several resonances within the desired operating band [19].

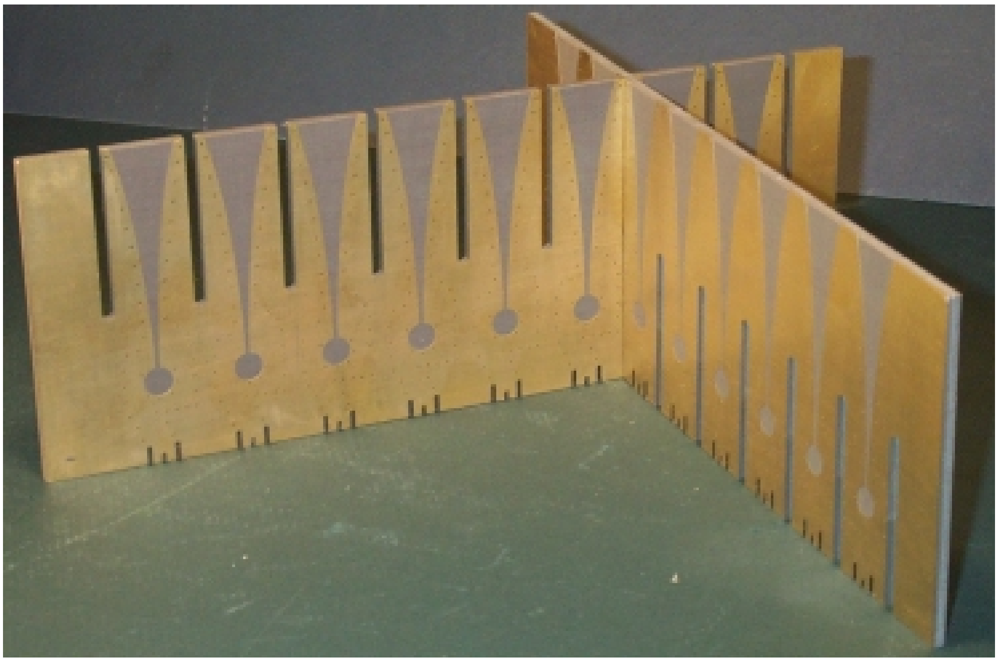


Figure 10. Fabrication using intersecting boards

Fabrication of an array with metallic posts as depicted in Fig. 5 can be very tedious. A successful array has been fabricated by using plated through vias to partition the substrate into individual elements. The array was then fabricated by joining orthogonal substrates and soldering the metallic ground planes together where the boards intersect. Two intersecting boards are displayed in Fig. 10. The assembly and soldering process is tedious and the resulting array cannot be repaired by replacing a single element. Easily manufactured and repaired arrays remain a challenge.

6 Summary

Arrays of Vivaldi notch antennas operating over multiple octaves are possible, provided the elements are designed properly and anomalies in performance are avoided. Numerical analyses are available that permit evaluation of proposed designs prior to fabrication. Numerical studies are providing insights into the mechanisms that cause arrays to perform poorly, and parameter studies are showing the pathways to successful designs. Single- and dual-polarized arrays have been designed to cover 5:1 bandwidths with SWR < 2 over all scan angles to 45°. Further study of array polarization and of means to extend the operating frequency will enhance the capabilities of these arrays. Improvements in design of the arrays for manufacturing and maintenance are needed and will come from further work on these antennas.

Acknowledgement

This work was supported in part by the NFRA-ASTRON.

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