Low-Profile Conformal Circular Beam-Steering Array with Ultra-Broad Instantaneous Bandwidth

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Abstract – **This paper reports continued development of an ultra-broadband smart beam-steering circular array antenna with parasitically excited surface waveguides for low cost. The array has a low profile and is conformable to platforms, with a directivity of 5 to 10 dBi. Its steered beam and null cover full 360° azimuth angles. Significant progress has been made in expanding the array's instantaneous bandwidth from 20–250 MHz to about 1000 MHz, which is an octaval bandwidth of 2:1 over the operating range of 1–2 GHz.**

1 INTRODUCTION

The proliferation of wireless systems in recent years, such as various wireless LANs, has created a large and growing need for smart beam-steering antennas of 5 to 10 dBi directivity with full 360° azimuthal coverage. Since conventional beam-steering arrays are very expensive, a major focus has been in parasitic arrays. However, most of the published research in such a circular array has been focused on narrowband null-steering applications for which the bandwidth and beam issues were often not addressed [e.g., 1-2]. Other designs may be bulky and complex [e.g., 3].

Recently the authors presented a parasitic circular array having an operating frequency range of 1–2.5 GHz with an instantaneous bandwidth of 20–200 MHz [4 and 5]. The array consists of a center driven element and a cluster of surface waveguide elements symmetrically positioned in the periphery and parasitically excited to achieve electronic beam forming in azimuth, with a steerable beam as well as steerable nulls. Its physical configuration is attractive for most real-world applications, which generally require low profile and platform compatibility. In this paper, we will present recent progress in expanding its instantaneous octaval bandwidth to 2:1.

2 THE DESIGN APPROACH

The limitation of the instantaneous bandwidth of the array in [4] is primarily rooted in its surface waveguides. Therefore, the present design effort for the array began with a focus on the surface waveguide. Since this is a complex problem involving both the design of the microwave structure and the interference effects of the switching circuit, we broke the design task into two steps: the static breadboard model and the electronically steered model.

The basic structure of the surface waveguide investigated in this effort is depicted in Figure 1, which is a log-periodic (LP) structure. The LP structure is a well-known broadband configuration in which the heights and spacings of the switchable conducting elements follow an LP pattern for the frequency range of interest [4, 5 and 6].

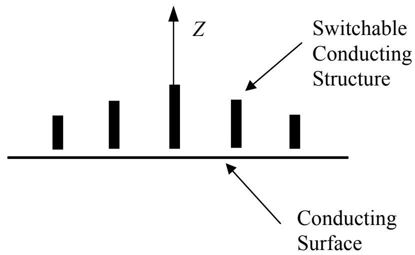

Figure 1: A broadband LP surface waveguide.

After a suitable static array model had been developed, switching circuits were implemented in the surface waveguide to realize a full electronically steered array, which was then tested and optimized. This two-step approach enables us to visualize more directly and precisely the intervening design problems as just discussed, whose complexity was further compounded by the large bandwidth and beam steering features.

3 THE STATIC MODEL

First, we designed, fabricated, and tested a series of static models for the surface waveguide shown in Figure 1. In the static models, the "on" and "off" states of the switches (currently p-i-n diodes) in the surface waveguides were simulated with the presence and absence of gaps and "no gaps", respectively, in the switchable conducting structure. These surface waveguides, each with a row of switchable conducting "rods," were embedded in PC boards for structural integrity and, above all, low-cost fabrication. The static surface waveguides on PC boards were then assembled into the array for

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testing.

One of the array models made of static surface waveguides showed very promising results from 1.07 GHz up to 3 GHz (the highest frequency at which data was collected). Figure 2 shows measured SWR over 1-2.5 GHz for a beam state, which is < 3:1 over an instantaneous bandwidth over 1.07–2.37 GHz.

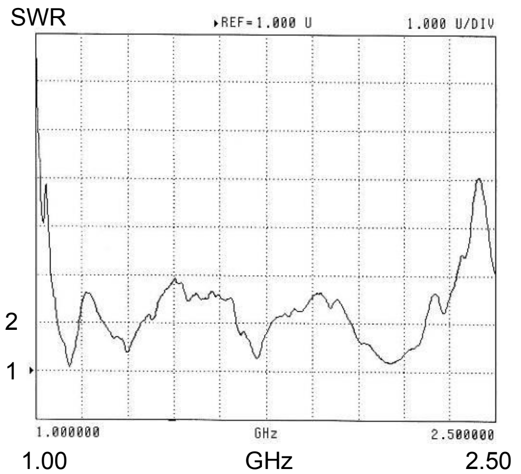

Figure 2: Measured SWR over 1–2.5 GHz.

Measured azimuth and elevation radiation patterns, in 5 dB/div, on this static model over 1000–1950 MHz are shown Figures 3 and 4, respectively.

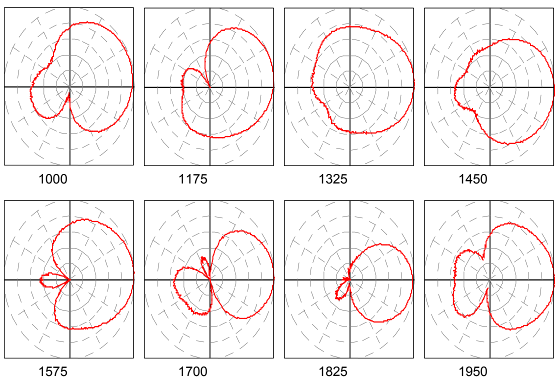

Figure 3: Measured azimuth radiation patterns.

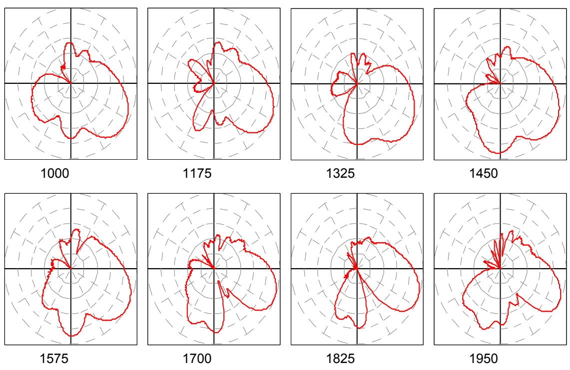

Figure 4: Measured elevation radiation patterns.

The antenna patterns are vertically polarized, with minimal cross polarization. (The plane of the disk-shaped array is parallel to the ground.) This set of pattern data is for beam state number 1, which is directed in an azimuth direction to the right side of the paper in Figure 3. In the elevation patterns in Figure 4, the beam is also directed to the right side of the paper, with a downward tilt because the antenna is to be mounted on the belly of a flying vehicle. Due to the symmetry of the array in the azimuth plane, the patterns in Figures 3 and 4 represent typical measured patterns for all other beam states as well.

Measured peak antenna gain for beam number 1 is shown in Figure 5. As can be seen, it is 5–9 dBi over most of the 1.05–2.4 GHz band. The performance of this array, including SWR, pattern and gain, for other beam states is in principle similar because of its circular symmetry about the antenna axis (or the azimuth plane).

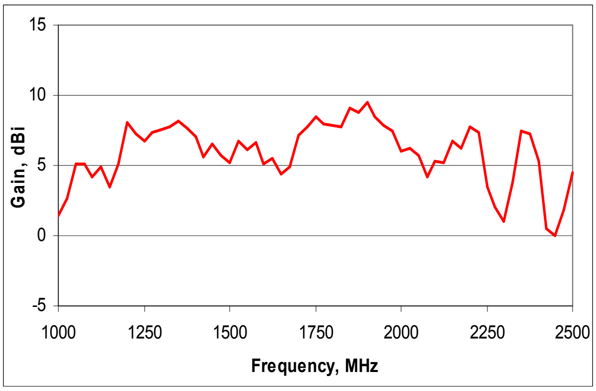

Figure 5: Measured peak elevation gain.

Although this static model has not yet been optimized–and obviously it can be considerably improved with further optimization–it is sufficiently adequate as a basis for the next stage: implementation into the electronically steered array.

4 THE ELECTRONICALLY STEERED MODEL

The bulk of the development effort in moving from the static model to the dynamic model was in designing the RF impedance switching circuits and the associated bias circuits, and to ensure that it would not negatively impact the performance achieved in the static model. The beam-steering software and the beam-steering computer (BSC) interface in [4] were also redesigned to improve its speed and reliability.

Figure 6 is a photographic display for the assembly of a complete dynamic electronically-steered array, including the array structure per se, BSC, dedicated GPS/INS subsystem, and software.

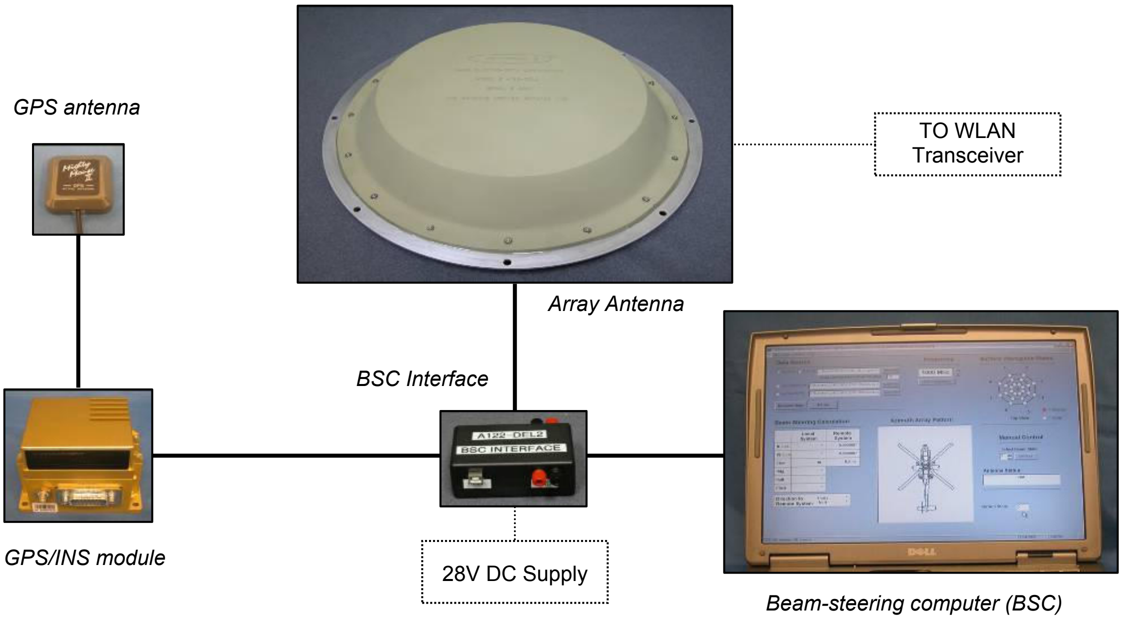

Figure 6: Assembly of a complete electronically-steered array.

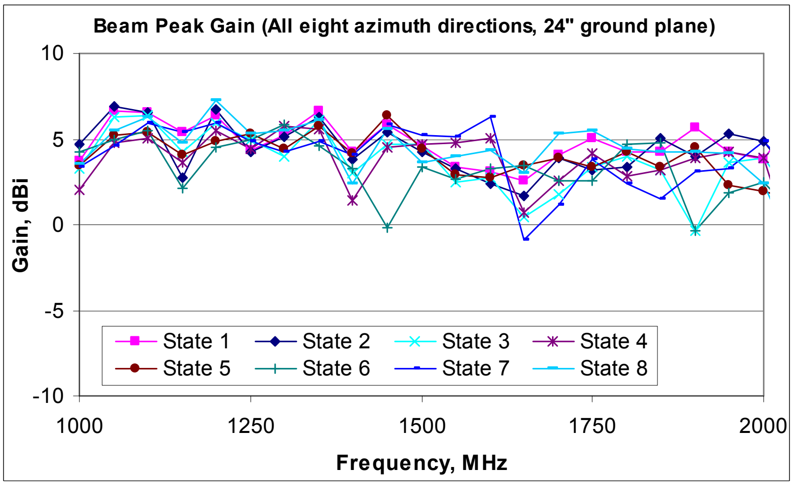

Figure 7: Measured antenna gain for electronically steered array.

The complete electronically-steered array in Figure 6 has gone through comprehensive laboratory tests in WEO's anechoic chamber. A summary of the test results is highlighted here. The array patterns exhibited 5 to 10 dBi directivity over large portions of the 1-2.5 GHz range, with poor directivity over 1400–1600 MHz. The antenna patterns are vertically polarized, with minimal cross polarization.

There are some undesirable back lobes, which are due in large part to the relatively small size of the ground plane used in the measurements (24" diameter). These back lobes can be reduced when the antenna system is mounted on a platform with a larger ground surface.

Measured antenna gain in dBi at the beam peak for all eight azimuth beam states with the antenna mounted on a 24"-diameter ground plane are shown in Figure 7. States #1, 2, … 8 correspond to beam directions $\varphi = 0°, 45°, \ldots 315°$, respectively, in the azimuth plane. The antenna gain is observed to be generally 2 dB, sometimes 5 dB, lower than the antenna directivity based on the antenna patterns. It is estimated that there is about 1 to 2 dB loss due to the switching circuit, and the rest of the loss is due to impedance mismatch (which is compounded by the effects of the switching circuit).

When compared with the performance of the static models, we believe that improvements, especially at the worst-performing frequencies, can be readily achieved, as will be discussed in the next section. Furthermore, optimization of the surface waveguide control states in the beam-steering software would add more improvement.

At present, the array has only low to moderate antenna gain, which is adequate for enhancing signal-to-noise ratio essential for wireless LAN applications. If needed, a higher antenna gain (over 10 dBi) is feasible by increasing alignment of the phase fronts of adjacent surface waveguides.

5 THE SWITCHING CIRCUIT

As discussed earlier, the switching circuit of the surface waveguides of the array suffers from the interference of the bias/control circuit with the RF circuit/waveguide. We believe that a major contributing factor in the problem was in the lumped circuit elements (chip diodes, inductors and capacitors) employed in the RF switching circuit in the surface waveguide and the control/bias circuit. For frequencies below about 2 GHz, lumped elements are generally effective in isolating the bias/control circuit from interaction with the RF circuit. At frequencies about 2 GHz and higher, these chip components can become complex circuits, losing their intended functions and even causing disruptive effects.

The difficulties and complexities in the design problem cannot be attributed only to the deficiencies of the components at higher frequencies, but also to the inherent design difficulties in broadbanding; the broader the bandwidth, the more severe the problem becomes. As the RF switching circuit elements deviate more than expected from ideal open-circuit and short-circuit conditions, they would require additional compensation to tune the combined surface waveguides and switches. And the problem becomes more difficult as the bandwidth increases.

In order to cover an ultra-broad 2:1 bandwidth, we generally employed two diode switches in each conducting "rod" in the surface waveguide in Figure 1. As a result, the control/bias circuit becomes more complex.

The use of photonic or MEMS switches in place of the diodes currently used in the surface waveguides has been found to be promising for performance enhancement. Also, the design on switching subsystem for the present array can benefit from the research in the reconfiguration of antennas, which is a much more complex problem.

Indeed, research in antenna reconfiguration has been carried out at several major institutions based on the fabrication of new electromagnetic materials. Techniques are available which can turn substrates into either conductors or nonconductors using non-intrusive techniques such as optical control. These switches can work at frequencies up to 10 GHz, and maintaining RF current of 1 amp. They have been applied to densely packaged planar array antennas, which are much more complex and difficult to switch than the present circular array. We plan to apply these techniques to the present array in the near future.

Although a topology for the bias circuits that would minimize interference with the RF phasing had yet to be found, these problems are in the implementation of the design, not in the fundamental approach. We believe it can be overcome with the techniques discussed above.

6 CONCLUDING REMARKS

A two-step design approach, from static to dynamic models, was taken in an effort to expand the instantaneous bandwidth of a circular parasitic array. Significant progress has been made in expanding the circular array's instantaneous bandwidth from 20–250 MHz to about 1000 MHz, which is an octaval bandwidth of 2:1 over the operating range of 1–2 GHz. However, this claim is primarily based on findings in a static model; test results on the electronically steered dynamic model were not as good. The two-step design approach enables us to believe that the discrepancies between the static and dynamic models are mainly due to the impact of the switching circuits.

This array is low-profile, suitable for conformal mounting on most platforms, such as automobiles, aircraft, etc. Another major advantage of this array is its low fabrication cost, which is estimated to be an order of magnitude lower than that of conventional beam-steering arrays with similar functionality.

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