Design and Testing of a Feed Network for a Transparent Antenna Array

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Abstract

This paper describes the design and testing of a feed network for a transparent flat-plate array antenna. This antenna is the top of a stack of three antennas that must occupy the same volume while pointing in different directions. At many pointing angles, an antenna will create blockage for the antennas underneath. In order to minimize the blockage, the array and its transmission lines must be as transparent as possible to the antennas underneath.

The flat-plate array consists of active elements over a frequency-selective surface (FSS) ground plane that is transparent at the frequencies of the antennas below it. The feed lines must also be transparent to the antennas below it. This is achieved by minimizing the total area occupied by the feed lines. Rather than the traditional corporate feed network, a series feed network was designed. Such a network requires that each individual feed point must be fed with a coupler, where the coupling coefficient is adjusted to distribute the same power to each array element. We show the details of the design of the network as well as a set of measurements that show the performance.

Keywords: Antenna array feeds; antenna arrays; antenna measurements; antenna tolerance analysis; microstrip directional couplers; frequency selective surfaces; transmission lines; planar transmission lines

1. Introduction

For a new type of communications antenna system, three antennas had to occupy the same volume while pointing in different directions [1]. At many pointing angles, the antennas above will create blockage for the antennas underneath, as seen in Figure 1. In order to minimize the blockage, the array and its transmission lines had to be as transparent as possible to the antennas underneath.

Each antenna was a flat-plate array that consisted of active circularly polarized elements over a frequency-selective surface (FSS) ground plane, which was transparent at the frequencies of the antennas below. The traditional corporate feed is a common feed network for antenna arrays. However, a corporate-feed network occupies a large surface area with its feed lines. A new type of series-feed network was developed that minimizes the total area occupied by the feed lines.

We will show the details of the design of the network, as well as a set of measurements and simulations that demonstrate the performance.

2. Feed Network

The feed network (shown in Figure 2) was a star-shaped series-transmission-line structure, designed to reduce the blockage presented to the underlying antennas. The transmission line was located in a layer behind an FSS ground plane and the active elements. This transmission line utilized four quarter panels that could be fed with a four-way power divider, or that could be used for monopulse tracking.

Each quarter panel consisted of a main line (ML in Figure 3) and six branch lines (BL1, BL2, BL3, BL4, BL5, and BL6 in Figure 3) of multiple lengths. The main and branch lines both consisted of a number of couplers connected in series, with the coupled port of the coupler going to an output and the through output being connected to the input of the succeeding coupler. Each output of the main line was connected to a single branch line. Each branch-line output was connected to a radiating element via a vertical microstrip transmission line.

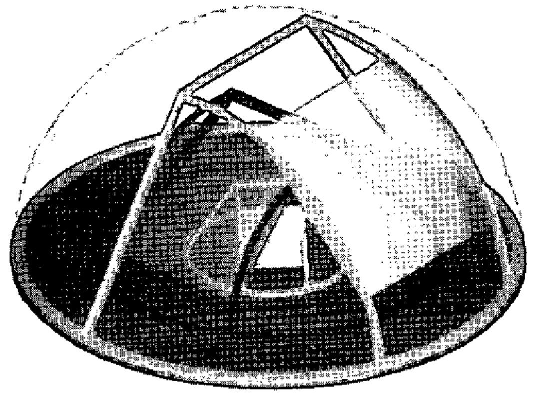

Figure 1. A concept drawing of the nested antennas [1].

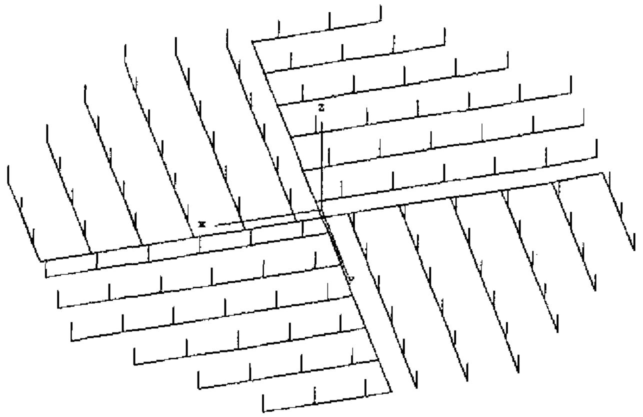

Figure 2 The full feed network.

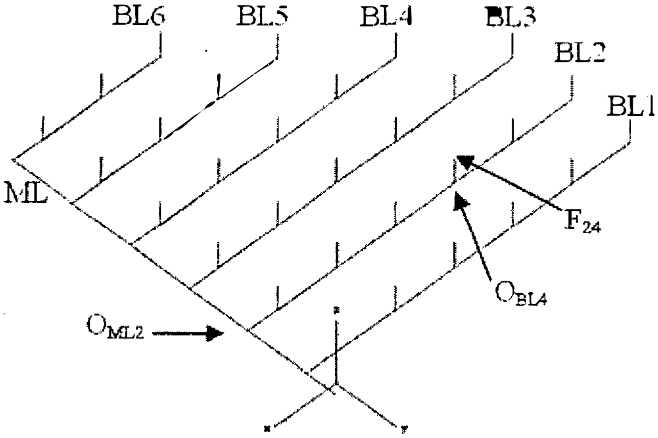

Figure 3. A quarter panel of the feed network.

Table 1. The main trunk coupling.

Connected Branch Line BL_m	Fed Elements/ Branch	Coupling C_{MLm} (dB)	Through T_{MLm} (dB)	Output O_{MLm} (dB)
BL1	6	-6.99	-0.97	-6.99
BL2	6	-6.02	-1.25	-6.99
BL3	6	-4.77	-1.76	-6.99
BL4	5	-3.80	-2.34	-7.78
BL5	4	-2.43	-3.68	-8.75
BL6	3	0	-Infinity	-10.00

Table 2. The branch line coupling.

n	Coupling C_{BLn} (dB)	Through T_{BLn} (dB)	Output O_{BLn} for $m =$			
			1,2,3	4	5	6
1	-7.78	-0.79	-7.78	n/a	n/a	n/a
2	-6.99	-0.97	-7.78	-6.99	n/a	n/a
3	-6.02	-1.25	-7.78	-6.99	-6.02	n/a
4	-4.77	-1.76	-7.78	-6.99	-6.02	-4.77
5	-3.01	-3.01	-7.78	-6.99	-6.02	-4.77
6	0	-Infinity	-7.78	-6.99	-6.02	-4.77

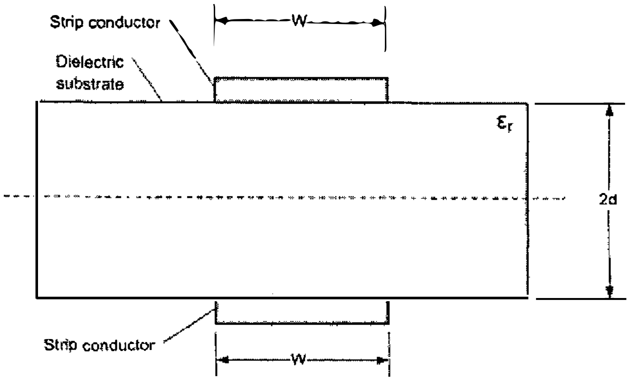

Figure 4. Parallel strips used for the transmission lines.

This type of network required a coupler wherein the coupling coefficient can be adjusted to distribute the same power to each array element. The power division had to be carefully calculated, in order to ensure that equal power was delivered to the individual elements (see Tables 1 and 2).

The main-line output, O_{MLm}, was connected to BL_m, and can be calculated from the individual coupling and through outputs as below. Likewise, the branch-line BL_m output, O_{BLn}, was connected to the feed-point output, F_{mn}:

$$O_{MLm} = C_{MLm} + \sum_{1}^{m-1} T_{MLi},$$

$$O_{BLn} = C_{BLn} + \sum_{1}^{n-1} T_{BLj},$$

$$F_{mn} = O_{MLm} + O_{BLn}.$$

The units for the above equations are dB. Using the above equations yielded a result of–14.77 dB for each feed-point output, F_{mn}.

The transmission lines were printed on both sides of a layer of low-loss substrate to reduce blockage (see Figure 4). Each side was identical. It is a simple exercise to use image theory to demonstrate that this is similar to the traditional method of printing microstrips over a ground plane [2]. This method provided a balanced transmission line to feed the radiating elements, eliminated a ground plane that would degrade transmissivity, and allowed us to control the transmission-line impedance in order to obtain a good match between the transmission lines and the active elements.

3. Couplers

Multiple types of couplers were considered as the basic building block for the feed network. The only restriction on the type of coupler was the ability to achieve the tight coupling requirements. Two-line [3, 4] and Lange couplers [5] were used in early designs.

A two-line coupler (see Figure 5) was the initial coupler considered. The coupling ratio for a two-line coupler is dependent on the separation between the two horizontal lines (S in Figure 5). A prototype was fabricated using two-line couplers, as shown in Figure 6. It utilized four couplers in series, in addition to a through port.

Data from the two-line coupler transmission line is given in Table 3. Note that the designed values for this transmission line differed from the values given in Table 2. This was done due to the inability of the two-line coupler to achieve extremely tight coupling. The design required a separation of 3 mils in order to achieve the required coupling performance. The minimum spacing specified by most PCB (printed-circuit board) fabrication facilities is 3 mils. The design also required a relative dielectric of 10.2, with a thickness of 0.25 inches. The high dielectric constant and thickness of the substrate presented a significant problem for transmissivity.

The quadrature hybrid coupler (see Figure 7) was an alternative that is typically configured as a 3 dB directional coupler. We could control the coupling ratio between the through and coupled outputs by adjusting the widths, W_A and W_B [6]. Widths W_A and W_B were calculated from impedances Z_{0A} and Z_{0B} (given below), using standard microstrip design formulas [3]. P_A and P_B are the linear power outputs for the coupled and through outputs, respectively.

$$Z_{0A} = Z_0 \left(\frac{\frac{P_A}{P_B}}{1+\frac{P_A}{P_B}} \right)^{1/2},$$

$$Z_{0B} = Z_0 \sqrt{\frac{P_A}{P_B}}.$$

The quadrature hybrid coupler was simulated using Agilent Design Software's *Momentum*, which uses a Method of Moments (MoM) technology to analyze the circuits. The design formulas yielded results with less than a 0.25 dB difference from the desired coupling values. An iterative process was used to adjust the coupler dimensions to better match the ideal coupling. The final coupler values and simulation results are given in Table 4 and Table 5.

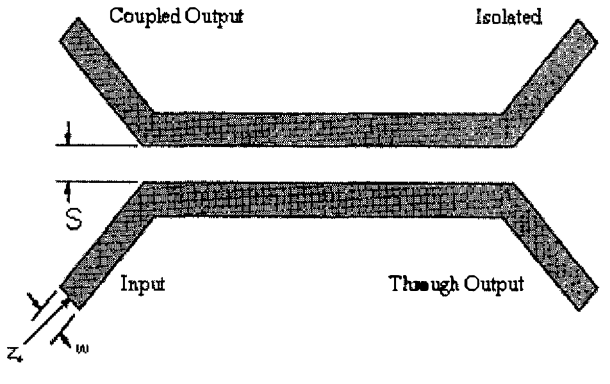

Figure 5. A two-line coupler.

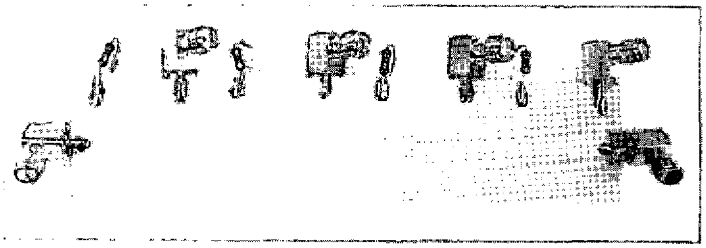

Figure 6. The transmission-line prototype.

Table 3. The measured coupler data.

Port	Designed (dB)	Measured (dB)	Δ (dB)
Through	-4.01	-5.61	-1.60
S21	-8.74	-8.67	0.07
S31	-8.73	-8.56	0.17
S41	-8.57	-9.12	-0.55
S51	-8.40	-8.09	0.31

Table 4. The main-line coupler simulation results.

m	Z_{0A} (Ω)	Z_{0B} (Ω)	C_{BLm} (dB)	T_{BLm} (dB)
1	44.54	98.06	-7.11	-0.94
2	43.09	84.91	-6.11	-1.22
3	40.57	69.42	-4.85	-1.73
4	37.91	58.14	-3.85	-2.31
5	32.73	43.30	-3.60	-2.50

Table 5. The branch-line coupler simulation results.

n	Z_{0A} (Ω)	Z_{0B} (Ω)	C_{MLn} (dB)	T_{MLm} (dB)
1	45.52	110.02	-7.80	-0.79
2	44.54	98.06	-7.11	-0.94
3	43.09	84.91	-6.11	-1.22
4	40.57	69.42	-4.85	-1.73
5	35.35	50.00	-3.10	-2.92

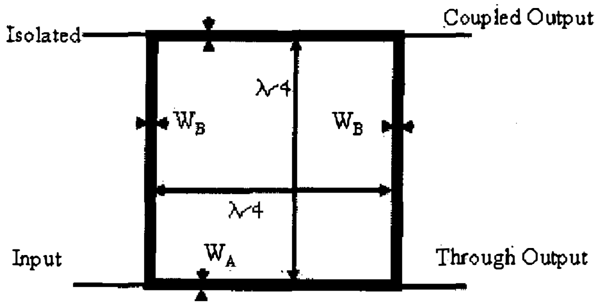

Figure 7. The quadrature hybrid coupler.

By using a quadrature hybrid coupler as the basic building block, we could use a substrate with a relative dielectric constant of 2.2 and a thickness of 0.031 inches, a substantial improvement over the two-line coupler substrate. A full transmission-line structure utilizing a quadrature hybrid coupler is currently being fabricated.

4. Transmissivity

A 2230 MHz array of active elements looking through the L-band transmission-line structure was modeled (see Figure 8), using a wire-grid Method of Moments (MoM) code developed at OSU [7, 8]. The model was very accurate; however, simulation runs could take several days (Pentium IV 3.0 GHz, 1 GB RAM), depending on the simulation parameters.

The transmission-line structure was rotated with respect to an axis set behind the 2230 MHz active elements. The 2230 MHz array was stationary. The maximum deviation from the free-space boresight gain of the 2230 MHz array was 0.16 dB at ±5° rotation.

5. Phase Distribution

In contrast to a corporate-feed system, this transmission-line design resulted in an unequal distribution of phase to the feed points, due to different distances between the input and the individual feed point for the radiating elements. In order to achieve equal phase for each radiating element, we could compensate by rotating the circularly polarized radiating elements. The vertical stub between the active elements and the branch-coupler output is a turn in the microstrip transmission line. In order to accommodate the rotated circularly polarized elements, the microstrip transmission line and the substrate were twisted with respect to the plane of the couplers. The substrate chosen (Rogers Duroid 5880) retained the deformation without any resistance.

The method of rotating the circularly polarized antennas was demonstrated on a 1 × 4 array (see Figure 9). The phase of each element was measured by using a small loop antenna and disconnecting the remaining three antennas (see the top half of Figure 10). The phase of the rotated antennas is given in the bottom half of Figure 10.

Note that the individual measured phases of the un-rotated elements‘a’and‘b’were equal. Observe that in Figure 9, the left two elements were rotated by the same amount. The measured phase of each rotated element was nearly equal at the design frequency of 1695 MHz (see the bottom half of Figure 10). For the final layout, each of the circularly polarized elements will be oriented such that all of the radiated circularly polarized signals are in phase.

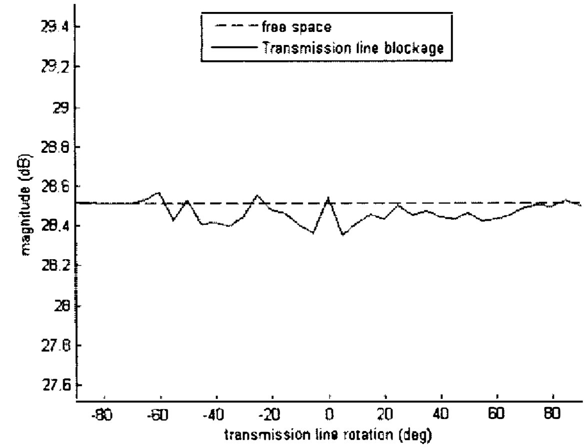

Figure 8. The magnitude of the signal from the S-band array looking through the transmission-line structure.

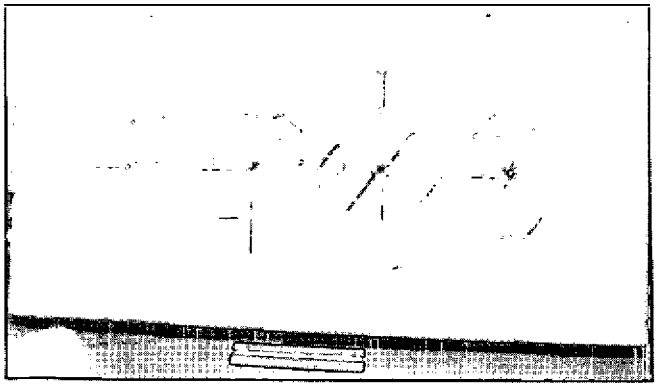

Figure 9. The rotated elements: (l-r) elements a, b, c, and d.

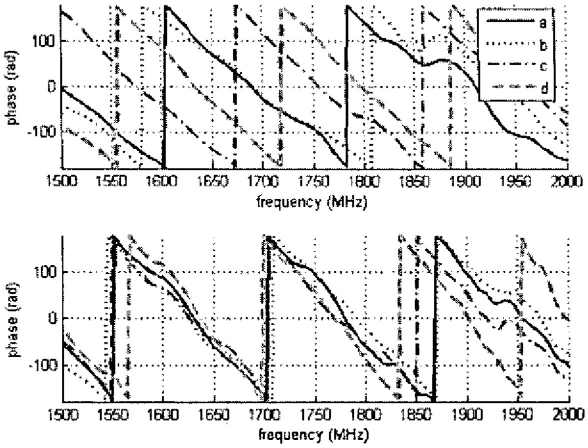

Figure 10. The phase-measurement data: un-rotated antennas (top), rotated antennas (bottom).

6. Summary

The design and data were presented for a 12 × 12 L-band array. The same concept was utilized for an underlying 14 × 14 S-band array. Full transmission-line structures using the quadrature hybrid coupler for the L and S band are currently being fabricated. Data on the new transmission-line structures is expected in August 2005.

The three-antenna structure is presently under construction. When completed, it will be possible to have three antennas operating independently in a single radome occupying the space normally needed for each of the three antennas. New data on the performance of the overall antenna structures will be available in early 2006 (a provisional patent has been filed).

8. Acknowledgments

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9. References

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Editor's Comments *Continued from page 137*

the journal in which the accomplishments are published to measure the value of such accomplishments makes sense.

We have a long-standing, well-tested method of judging the significance and value of engineering and scientific accomplishments: it's called peer review. I believe it can work equally well for judging tenure, promotion, compensation, and reward. It doesn't have the impersonality of a formulaic approach, but that is also part of its strength. Applying peer-review methods to judging accomplishments must be done carefully, and it often should involve including review by those outside of the institution or organization involved, in order to reduce the effects of potential biases. It used to be the most common method used, and it may still be. I think the trend toward trying to "objectify" such evaluations comes from the misguided idea that we can quantify engineering or scientific achievement in much the same way that we try to test learning in courses. The problem is that what we should be trying to measure – usually, the value of an accomplishment – is often best measured in terms of the relative impact on a field and on the other workers in a field. That inherently involves judgment. The connection to Impact Factor of the journal in which the accomplishment is published is tenuous, at best.

There are larger issues involved in all of this, of course, and I'm sure those of you who have read this far will be relieved to discover that I'm not going to try to address them here. These have to do with the trend over the last few decades to give more and more weight to publications, as opposed to results and accomplishments (and the loss of understanding that there can often be a significant difference between a publication and a significant result or accomplishment). There are those who feel that the whole "publish or perish" process has become more and more flawed, and many of their concerns are valid (see, e.g., M. Gad-el-Hak, "Publish or Perish – An Ailing Enterprise?," *Physics Today*, **57**, March 2004, pp. 61ff; available online at http://www.physicstoday.org/vol-57/iss-3/p61.html). It is worth noting that I do not at all agree with everything in Gad-el-Hak's article. I simply offer it as an interesting commentary on a very complex problem.

Having written all of the above, what really matters are the quality of the articles in a publication, and how well that publication serves its readers. Impact Factor and Cited Half-Life have become important if only because they are some of the few measures that can be widely applied and, in some cases, compared. The *Magazine* is going to continue to try to bring you material of as high a quality and relevance as possible. And yes, if our Impact Factor and Cited Half-Life remain good, there will be pride in this, and concern if they do not. However, my belief is that ultimately authors show the value of a publication by submitting articles, and readers do the same with subscriptions. I'm very pleased and thankful that by those measures, the *Magazine* is doing extremely well, indeed.

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