High Efficiency Antenna Array With Optimized Corporate Hybrid Feed

Dan Busuioc[1], Amir Borji[1], Mahmoud Shahabadi[2] , and Safieddin Safavi-Naeini[1]
[1]*E&CE Department, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1*
[2]*Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran 14399*
Email: dbusuioc@uwaterloo.ca, Fax: (519)746-3077

Abstract

A low-cost *Ku*-band array of circularly polarized microstrip antennas benefiting from a low-loss waveguide feed network is demonstrated (patent pending). The 128 elements of the array which are arranged in a 4-by-32 configuration are subdivided into four 4-by-8 subarrays. To maintain feed losses and thus the overall noise temperature at a minimum, the subarrays are excited using a 1-by-4 corporate feed network of hollow metallic waveguides. Due to a low-loss foam substrate, the array elements show high circular polarization gain of 7.5 dBic and wide relative bandwidth of 4%. The measured circular polarization gain of the array amounts to 25.6 dBic with an aperture efficiency of 51% in the *Ku*-band of frequencies.

I. INTRODUCTION

Microstrip antenna arrays are exploited in a vast number of engineering applications due to their ease of manufacturing, low cost, low profile, and light weight [1]. In many practical designs, the elements of such arrays are fed by a coplanar corporate microstrip feed network in order to keep the overall constructional complexity at a minimum and maintain compact size [2]. At higher microwave frequencies, this approach, however, suffers from ohmic and dielectric losses of the connecting microstrip lines, as well as the undesired radiation of the feed network [3]. Realization of a high-efficiency microstrip antenna array having a large number of elements can be challenging, unless a low-loss low-radiation feed network replaces the coplanar one. Among all microwave transmission lines, hollow metallic waveguides feature extremely low losses up to very high frequencies and for this reason they have been intensively utilized in the special feed system of planar slot arrays [4], [5] and in the beam forming network (BFN) of satellite antennas [6].

Waveguide feed networks have also been combined with microstrip antenna arrays to enhance the overall radiation efficiency of the resulting hybrid arrays [7]. This method simplifies the feed network and at the same time provides a low-loss power distribution among the rows although its resonant nature reduces the operating bandwidth.

We realize a a high-gain, high-efficiency *Ku*-band array of circularly polarized microstrip antennas fed by a low-loss waveguide feed network. This corporate feed of rectangular waveguides with E-plane tees and bends form a novel, ultra-compact corporate feed for the microstrip array. Since only E-plane components are used in the feed network, it is manufactured from two waveguide halves that are secured together easily. Electromagnetic coupling between the waveguide feed network and the radiating elements is established using a low loss design for waveguide-to-microstrip transitions using coaxial probes.

II. DESIGN

The approach to antenna design consists of two parts – first of all the top layer microstrip substrate stack-up is determined based gain requirements and physical restrictions. Due to the high gain and bandwidth required, a thick, low-permittivity substrate is desirable. The substrate chosen was a 1.5 mm thick foam, with $\varepsilon_r = 1.047$ and $\tan\delta = 0.0017$ at f = 10 GHz. Since the copper radiating elements cannot be easily and accurately printed on the foam, a very thin, higher loss substrate material is chosen as a support for the array. As such, a very low cost, 0.05 mm thick FR4 material with $\varepsilon_r = 4.4$ and loss of $\tan\delta = 0.02$ at f = 10 GHz is chosen [1].

A. Antenna Array Elements

The patches chosen as radiating elements for this array are in the circular shape, with stubs and notches used to tune the two orthogonal electric field elements $E_{horizontal}$ and $E_{vertical}$ required for circular polarization.

1-4244-0123-2/06/$20.00 ©2006 IEEE

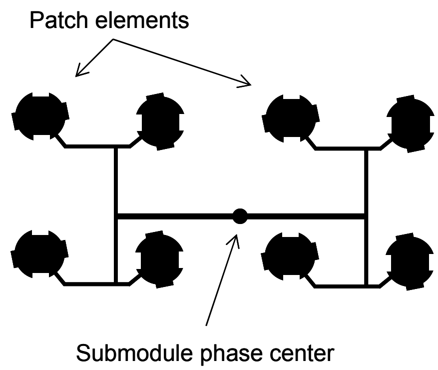


Fig. 1. Array submodule consisting of circularly polarized elements and top layer microstrip feed.

In Fig. 1 we illustrate a submodule of the proposed array, showing the 90° sequential rotation we thoroughly investigated in [1] to improve the axial ratio (AR) purity. Further details on the elements are given in [1].

B. Low-Loss Waveguide Feed

The second part of the design and the main discussion of this work consists of the low-loss waveguide feed and the optimization of the corporate feed distribution across the two technologies – waveguide and microstrip. The cost—performance tradeoffs must be considered for the waveguide feed, namely a more complex structure would incur a higher cost, while providing lower feed losses. Considering a total of N elements of a corporate—fed array, and realizing the complete feed as a cascaded system of power dividers, starting with waveguide power dividers feeding submodules of patch elements, and ending with microstrip power dividers feeding individual elements, we can write an equation of the form:

$$\log_2 T_{Wg} + \log_2 T_{Ms} = \log_2 E \tag{1}$$

where T_{Wg} is the number of waveguide outputs (or the number of submodules), T_{Ms} is the number of patch elements being fed by each submodule input, and E is the total number of elements in the array. In other words, Eq. 1 represents the number of 1:2 power dividers present in the system. Furthermore, if we define a 'cost' equation for the overall loss budget, we can write:

$$C_{T-Wg} \times T_{Wg} + C_{T-Ms} \times T_{Ms} = C_1 \tag{2}$$

and

$$C_{L-Wg} \times T_{Wg} + C_{L-Ms} \times T_{Ms} = C_2 \tag{3}$$

with

$$C_{total} = C_1 + C_2 + C_{other} \tag{4}$$

where $C_{T\text{-}Wg}$ and $C_{T\text{-}Ms}$ are the transmission losses (in dB) incurred in each of the waveguide and microstrip T power dividers, respectively, and $C_{L\text{-}Wg}$ and $C_{L\text{-}Ms}$ are the loss characteristics of the average length of transmission line for waveguide and microstrip, respectively. Therefore the total loss can be considered to be the sum of the power dividers and the individual line lengths, as well as another loss factor C_{other}, which is comprised of losses in the waveguide-microstrip transitions [1], as well as at the input plane of the waveguide.

Equations (2) – (4) only estimate the transmission dB loss estimation through the feed network, additional calculations need to be performed to obtain the dollar cost of transmission line implementation. These will be addressed in a future paper.

Based on simulation of waveguide and microstrip T junctions, as well as transmission line losses of different technologies, Table 1 can be obtained for a center frequency of 12.4 GHz.

With this it becomes apparent that the best feed technology can be had with each element being fed by a waveguide port; however this creates a bulky and extremely costly array. Therefore, using further optimization techniques, we consider a tradeoff between the waveguide and

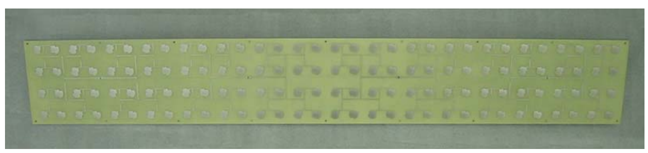
Table 1: Losses in the array feed at 12.4 GHz

	T-junction (dB each branch)	Line loss (dB/m)
WR-75 waveguide	0.19	0.8
Microstrip	0.25	4.5

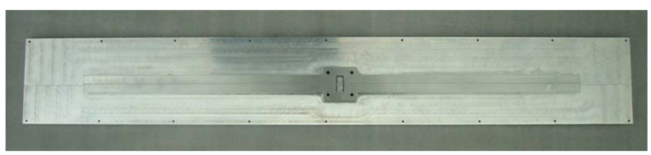
microstrip feed. The optimum cost/performance tradeoff results in a T_{Wg} = 4 (1:4 waveguide divider) and T_{Ms} = 32 (1:32 microstrip power divider). The design procedure undertaken is similar to what we reported in [1], and the completed waveguide feed consists of a WR-75 input flange, and two sets of 1:2 E-plane T power dividers, which are well matched for amplitude and phase output.

III. FABRICATION

Due to the overall configuration of the antenna (feed and elements) manufacturing can be done with two common manufacturing processes. First of all a standard PCB etching process is employed for creating the 2 mil FR4 substrate with elements on a single side. Separately, a milling of the two waveguide sections is done in a standard manufacturing shop. The proposed feed design does not suffer from tolerance errors and as such a low-cost milling process can be used. Finally, the entire antenna is assembled together in a lab/bench environment using common tools. A few dielectric screws are used to firmly attach the FR4 and foam layers to the waveguide which also acts as a ground plane for the elements. In a production unit, simple bonding could be used between the different layers to automate the assembly process.



(a)



(b)

Fig. 2. Complete manufactured antenna structure.
(a) front view. (b) back view, with WG-75 waveguide input

IV. MEASUREMENT RESULTS

The complete antenna is measured for input impedance in the lab, and furthermore its radiation

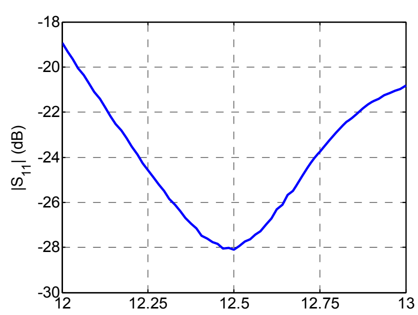


Fig. 3. Input matching of the 4x32 array.

characteristics are obtained on the far field range. First of all, Agilent VNA model 8722 is used to measure the S_{11} of the antenna and the result is illustrated in Fig. 3. We observe good input impedance match characteristics of $|S_{11}|$ < -24 dB over the desired 12.2 – 12.7 GHz range.

Although we could further optimize and extend this to a larger bandwidth, the degradation in radiation characteristics of the elements outside this GHz range adds little value to this bandwidth improvement.

The radiation of the antenna is measured and the far field plot at the center frequency is given in Fig. 4 we observe a total gain of 23.056 dB (linear spinning mode). Once adjusted for AR of better than 1.2 dB, which is not illustrated, the circular gain obtained is ~25.6 dB. This represents an aperture efficiency of better than 51%. Very slight asymmetry is present in the side lobe levels due to the un-symmetry of the microstrip feed system, as was illustrated in Section A.

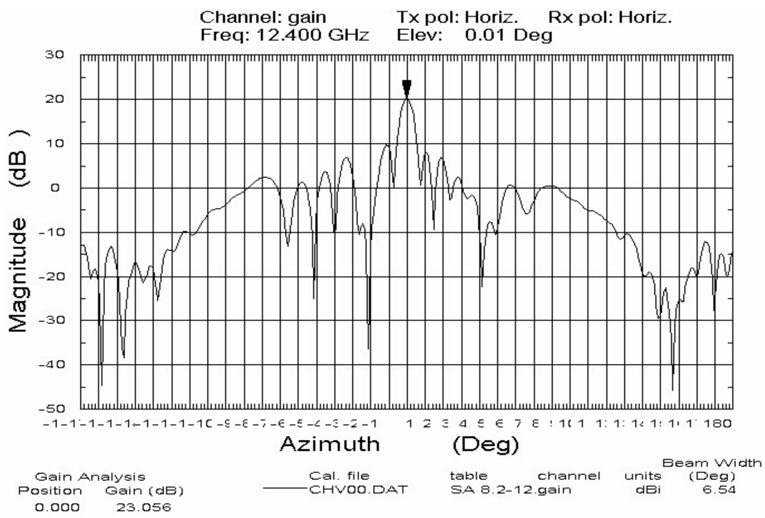


Fig. 4. Far field measurement results.

IV. CONCLUSION

We have presented a novel feed optimization mechanism for high-gain array antennas. The techniques discussed here have been used to design, develop, manufacture, and measure a complete 4x32 array antenna. The complete structure has a 25.6 dB gain and a 51% aperture efficiency and a bandwidth of >4%. The authors will further discuss the feed optimization algorithms which were used to achieve such a high gain and efficiency in a future paper.

V. ACKNOWLEDGEMENT

The work was supported by NSERC and CITO/OCE Tech Accelerator program.

REFERENCES

[1] M. Shahabadi, D. Busuioc, A. Borji, and S. Safavi-Naeini, “Low-cost, high-efficiency quasi-planar array of waveguide-fed circularly polarized microstrip antennas,” *IEEE Trans. Antenna and Propag.*, vol. 53, pp. 2036–2043, Jun. 2005.

[2] P. S. Hall and C. M. Hall, “Coplanar corporate feed effects in microstrip patch array design,” *Proc. Inst. Elect. Eng.*, pt. H, vol. 135, pp. 180–186, Jun. 1988.

[3] E. Levine, G. Malamud, S. Shtrikman, and D. Treves, “A study of microstrip array antennas with the feed network,” *IEEE Trans. Antennas Propag.*, vol. 37, no. 4, pp. 426–434, Apr. 1989.

[4] S. R. Rengarajan, “Compound coupling slots for arbitrary excitation of waveguide-fed planar slot arrays,” *IEEE Trans. Antennas Propag.*, vol. 38, no. 2, pp. 276–280, Feb. 1990.

[5] J. Hirokawa and M. Ando, “45 linearly polarized post-wall waveguide-fed parallel-plate slot arrays,” *Proc. Inst. Elect. Eng. Microw. Antennas Propag.*, vol. 147, pp. 515–519, Dec. 2000.

[6] L. Accatino, B. Piovano, and G. Zarba, “Reduction in size and weight of waveguide beam forming networks for satellite applications,” in *Proc. Antennas and Propagation Soc. Int. Symp.*, vol. 3, pp. 1996–1999 , Jul. 1996.

[7] W. Menzel, M. Schreiner, R. Mack, and P. J. N. Vera, “Millimeter-wave microstrip antenna arrays with waveguide feed network,” *Frequenz*, vol. 55, pp. 11-12, 2001.