W-band Amplitude-only Direction Finding with Curved-Aperture Horn Antennas

Jake Cazden, Muhannad Al-Tarifi, Ljubodrag Boskovic, and Dejan Filipovic
Department of Electrical, Computer, and Energy Engineering
University of Colorado at Boulder, Antenna Research Group
Boulder, CO, USA, 80309-0425
{jake.cazden, muhannad.altarifi, ljubodrag.boskovic, dejan.filipovic}@colorado.edu

Abstract—This paper presents the design, fabrication, and performance of a W-band amplitude-only azimuthal direction finding antenna subsystem, designed to cover 75-110 GHz. The design utilizes curved-aperture pyramidal horn antennas to achieve near frequency independent radiation patterns over the band of interest, and 2-element linear arrays to increase receiver detection range. Two arrays are squinted apart by 30° to realize a high slope and near monopulse direction finding function.

I. INTRODUCTION

Direction finding (DF) and spectrum sensing technologies have pushed into increasingly high frequencies and ultrawide bandwidths in recent years. The design of systems to meet new requirements necessitates splitting desired bandwidths into manageable sub-bands, or utilization of frequency independent antennas [1]. At W-band, common direction finding designs like spiral antennas and log periodic antennas [1] run into prohibitive size and integration requirements due to tight tolerances and millimeter wavelengths. To account for this, direction finding designs at W-band make use of techniques like slotline feeds to tapered slot antennas [2] and waveguide fed horn antennas [3]. In this paper we focus on azimuth-only DF using linearly polarized antennas. In particular curved-aperture rectangular horn antennas, the basic principles of which were first described by Dewey and Hill [4], are designed for implementation in a DF system with near frequency independent radiation patterns, and thus a near frequency independent Direction Finding Function (DFF). The individual apertures are arrayed in a 2 element E-plane linear array to increase the system gain, and thereby the overall detection range of the receiver. Theoretical results are fully verified with measurements.

II. DESIGN AND CONSTRUCTION

It is desired to achieve a frequency-stable DFF, high gain across the field of view, and easy extension into larger linear arrays for further gain improvements without destabilizing the H-plane antenna patterns. Curved-aperture horn antennas are examined as a satisfactory fulfillment of these requirements, as they are typically small in the E-plane, demonstrate high gain, and show stable radiation patterns. Visible in Fig. 1 is the normalized linear radiation pattern, and the individual antenna element used.

The individual aperture is designed for minimum radiation pattern variation in the H-plane through running parametrics on H-plane angular width, E-plane aperture width, and horn radial length. To increase system gain without disturbing the H-plane patterns, the design is extended to an E-plane linear array of two elements. Due to the 3.8mm E-plane aperture width, grating lobes cannot be avoided in the E-plane radiation pattern; however, they do not have a significant impact on overall system performance. The apertures are separated by 0.4mm, so as to be manufacturable without increasing the size of the side lobes of the array significantly, as well as to reduce aperture distribution interactions between the two elements. To feed the adjacent elements, an internal waveguide 3-dB splitter is present in the design. The feed point is positioned such that two adjacent standard W-band waveguide flanges can be connected flush to the system. An internal 30° bend prior to the splitter enables the antennas to be squinted. The final result can be seen in Fig. 2. Visible in the simulated structure is the waveguide splitter and the 30° bend. The input bend and splitter were designed for minimum size, without negatively impacting return loss and radiation pattern stability.

The system is fabricated with Direct Metal Laser Sintering (DMLS) technology to allow for accurate manufacturing in spite of curves present in both the E-plane and H-plane,
making split block machining more challenging. In simulation, the individual arrays have a boresight gain of 15.3 to 18.2 dBi over frequency, and are well matched to below -17dB. These results can be seen in Fig. 3 and Fig. 4.

### III. DIRECTION FINDING

To perform amplitude-only direction finding on a received signal, the power received by each of the squinted antennas is expressed as a ratio in dB. As the antenna patterns are known, this ratio can be mapped directly to an angle of arrival in $\theta$. The region of the function over which this mapping is unambiguous or has a slope greater than a receiver required resolution in dB/degree is considered to be the system field of view. This can be simply expressed as:

$$\text{DFF}_{\text{dB}}(\theta) = 10 \log_{10} \left( \frac{A_{\text{right}}}{A_{\text{left}}} \right)$$

Where $A_{\text{right}}$ and $A_{\text{left}}$ are the received power measurements from the two antennas. The DFF with simulated patterns from HFSS can be seen in Fig. 5. In red, on the left axis, is the DFF, showing a mapping from angle of arrival to a ratio in dB. The highly linear region within $\pm 20^\circ$ of boresight is the system field of view. In gold and cyan, on the right axis, is the normalized antenna radiation pattern. As desired the radiation patterns are largely invariant with frequency; however, the interaction of the individual elements with the overall system is visible, with the antenna patterns beginning to diverge after approximately 30° off of each antenna’s maximum.
possible over frequency, minimizing the potential calculation time. As the DFF is largely frequency independent, the linear region within the FOV is easily fit to a single term polynomial. The error of this simple fit can be seen in Fig. 6, showing a value of less than 3.5° of error in Angle of Arrival within the linear FOV. This error is calculated as an absolute difference between the angle of arrival for a given power ratio and frequency, and the angle of arrival as calculated with a linear fit from the power ratio, with frequency information discarded.

Fig. 6. Error in DFF linear fit over frequency. Traces show 5GHz steps from 75-110 GHz.

IV. MEASURED RESULTS

With the system seen in Fig. 2 the DFF performs as expected. Seen in Fig. 7 is the measured behavior of the antenna arrays and the resultant DFF, showing the same nearly linear region within approximately 20° of boresight. The antenna patterns as shown are normalized to the maximum gain measured from either the left or right antenna, evaluated at each frequency. Due to printing inaccuracies, there are differences between the two individual antennas, which shows plainly as the right antenna has higher gain. The visible gap in Fig. 7 shows a maximum reduction in gain from the right left antenna of 0.8dB.

As can be seen in Fig. 8, the error of a simple 1-term polynomial fit for the measured data is less than 3° over the entire frequency range. This was again calculated as the absolute difference between the true angle of arrival in the measured DFF data and the calculated angle of arrival based on a given power ratio.

Fig. 7. DFF (red) calculated from left and right measured radiation patterns (gold, cyan). Traces show 1GHz steps from 75 to 110 GHz.

Fig. 8. Error in DFF linear fit over frequency. Traces show 5GHz steps from 75-110 GHz, other traces were omitted for figure clarity.

V. CONCLUSIONS

Shown in this work is a W-band direction finding antenna system based on a curved-aperture horn. Low error seen in measured results confirms both system performance as designed, and the utility of pattern invariance as an effective design principle for individual direction finding antennas. Further work remains in this area to reduce the impact of the full system on the patterns of the individual antennas and integration with the backend reciever.

REFERENCES