A Lightweight Planar Ultrawideband UHF Monopole Mills Cross Array for Ice Sounding

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***Abstract*—An electrically large ultrawideband ultrahigh frequency (UHF) monopole antenna array has been designed to sound up to 3 km of ice and meet the logistical requirements of transportation to arctic regions. The monopole array is comprised of 16 planar subarray modules, which in combination form a 16 m by 17 m Mills cross array configuration to maximize sensitivity and spatial selectivity in both cross-track and along-track directions. Each planar subarray module is 1 m by 2 m in size with a 6.35 cm thick rigid insulation foam panel separating the individual monopole elements from metal foil ground plane on the top such that the maximum radiation is directed to nadir. Each subarray panel consists of 4 by 8 circular monopole antenna elements with a spacing of 0.25 m. Each monopole element is printed on a 130 mm by 80 mm 62 mil FR4 board. The total weight of each subarray panel is 9 kg, making for very lightweight and low-profile antenna construction. The antenna array together with the radar system was deployed to the East Greenland Ice-coring Project site in August 2018 for demonstrating surface-based ice sounding at the UHF band.**

***Index Terms*—Mills cross array, ultrawideband (UWB) monopole, UHF radar.**

I. Introduction

IN ORDER to fully validate the concept of ice sounding at UHF frequencies and high-resolution imaging of internal layers down to the bottom of the ice sheets, a surface-based multichannel radar system operating from 600 to 900 MHz with a significantly higher loop sensitivity than previous airborne ice sounders has been designed and built [1]. From the link budget calculation, if we consider the two-way ice loss to be 90 dB (15 dB/km at 750 MHz), the radar would require a large antenna array with a two-way gain of 60 dBi and a peak transmit power of 800 W to sound ice with more than 3 km thick. The antenna array would also need to meet the logistical requirements of being transported to polar regions. This requires a lightweight and a low-profile design. The array also needs to be easily assembled and deployed in the field.

Conventionally, high-gain antennas such as Yagi–Uda antenna or patch antennas are used with ice sounding radars [2]. However, for the required gain at UHF band, Yagi–Uda antennas are too heavy and bulky to deploy in polar regions. On the other hand, simple patch antennas cannot meet our fractional bandwidth requirement of 40%. A new lightweight, high-gain, ultrawideband antenna array is required. The design, construction, and deployment of such an antenna array are described in this letter.

II. Antenna Design

A. Configuration

Radar sensitivity is directly proportional to its power-aperture product. Instead of using a filled aperture, we have designed a thinned array configuration to meet logistics constraints of operating in polar regions. Specifically, we have designed and constructed a 16 m × 17 m antenna array in a Mills cross configuration [3], [4] for use as the radar antenna that meets the gain requirement. Fig. 1 shows the antenna array configuration. The transmit (TX) array consists of 4 × 64 radiating elements while the receive (RX) array has 64 × 4 elements. All the elements of both arrays have the same E-plane orientation, which is along the direction of travel. Therefore, the electromagnetic wave transmitted by AT array can be received by CT array with narrow beam-width along both directions. Both the TX and RX arrays are divided into 8 subarray panels (each with 32 antenna elements), which are connected to the corresponding eight-channel radar transmitters and receivers, as described in [1]. For each subarray panels, the signal is further divided/combined using a standard multistage 1:32 Wilkinson power divider.

Fig. 2 shows the single antenna element, as well as two 32-element subarray panel configurations in the cross-track (CT) and along-track (AT) for transmit and receive, respectively. The

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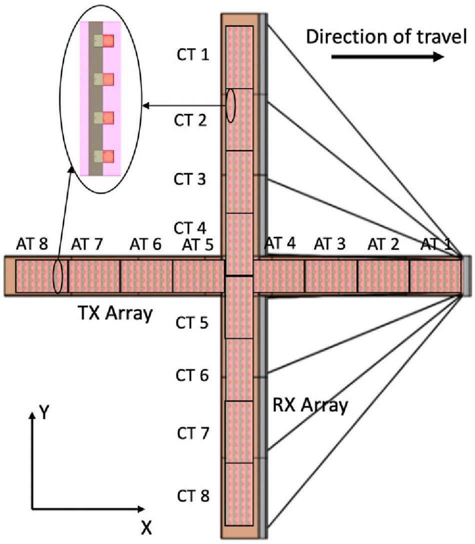

Fig. 1. Proposed Mills cross antenna array configuration.

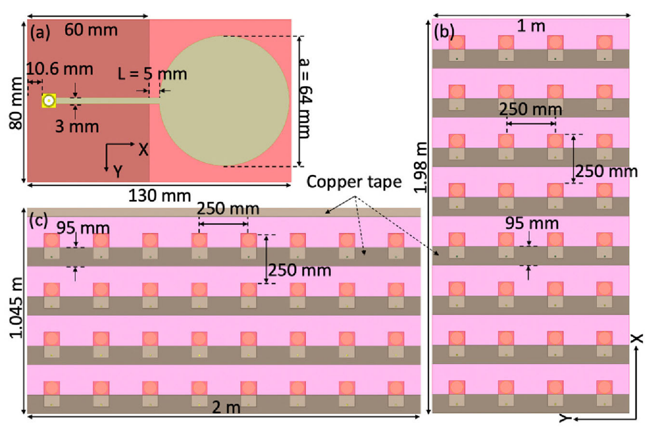

Fig. 2. (a) Printed single UWB monopole antenna element. (b) One 8 × 4 element subarray panel in the AT for transmit. (c) One 4 × 8 element subarray panel in the CT for receive.

required gain was achieved by adding a ground plane in the antenna panel 2.5” from the antenna elements. The CT panel is a transpose of the AT panel so that the transmit and receive polarizations are the same.

A circular monopole antenna design was selected for the 32 antenna elements in each panel as it is easy to achieve the required 300 MHz bandwidth. Each monopole element is 130 mm × 80 mm, which was fabricated using a standard 60 mil FR4 substrate. The effective dielectric constant of 60 mil FR4 is about 3.3 and the width of the 50 Ω microstrip feeding line is calculated to be 3 mm. The lowest operating frequency, which is about 600 MHz for the proposed design, can be calculated as

$$f_L = \frac{C}{4 \times (L + a)\sqrt{\varepsilon_r}}.$$

In the equation, C is the light speed, L is the length of the microstrip feeding line above the ground plane, a is the diameter of the circular monopole, and ε_r is the dielectric constant of the substrate. The more detailed description of the circular monopole dimensions can be found in [5] and [6].

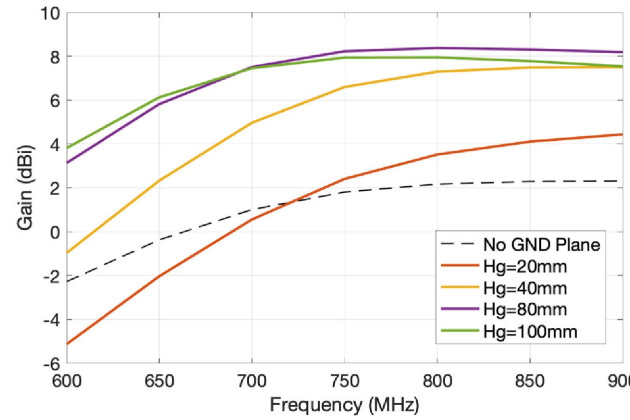

Fig. 3. Realized gain of a single UWB monopole element for various reflector spacing as compared to a standalone element.

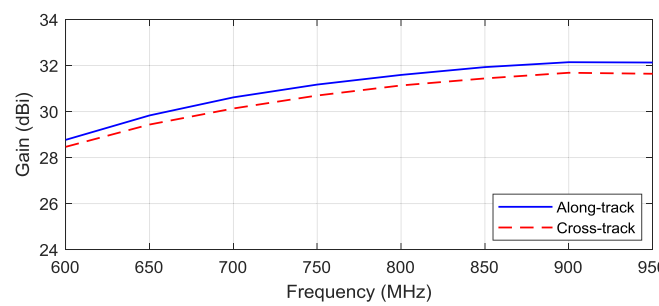

Fig. 4. Gain of full AT and CT arrays.

The antenna boards are bonded to a 2.5” thick rigid foam sheet that has planar dimensions of 1 m × 2 m. These dimensions are determined by monopole element spacing, which was optimally selected to be 0.25 m to obtain the maximum gain while avoiding grating lobes within the entire frequency band of operation. A sheet of aluminum foil is bonded to the back of the panel to act as a ground plane such that the maximum radiation is directed to the broadside direction (nadir). An aluminum foil stripe is also bonded on the top to connect the local ground planes of each monopole antenna element. Fig. 3 shows the gain of a single monopole element for various ground plane spacings (Hg) and without the ground plane present.

B. Simulation

The antenna array is simulated in ANSYS HFSS. An infinite array simulation was performed for the transmit array, which consists of 4 × 1 AT panels, and for the receive array, which consists of a 1 × 4 CT panels. The gain of a single 1 × 4 or 4 × 1 section was found to be approximately 13 dBi. Given the data, the gain of the CT and AT can be extrapolated using array theory. The gain curve for the two arrays is plotted in Fig. 4. The minor gain difference is due to the difference in the mutual coupling between the two array configurations. It can be seen that it is approximately 31 dBi for both transmit and receive arrays at the center frequency of 750 MHz. This gives a two-way gain of approximately 62 dBi, which meets our link-budget requirement.

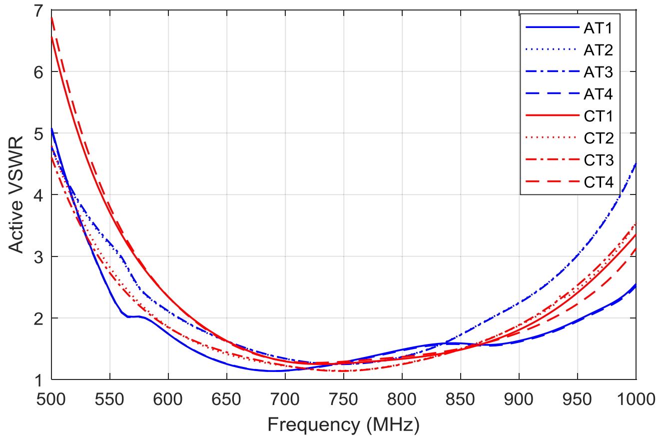

Fig. 5. Radiation pattern of the eight-panel AT array computed using array factor.

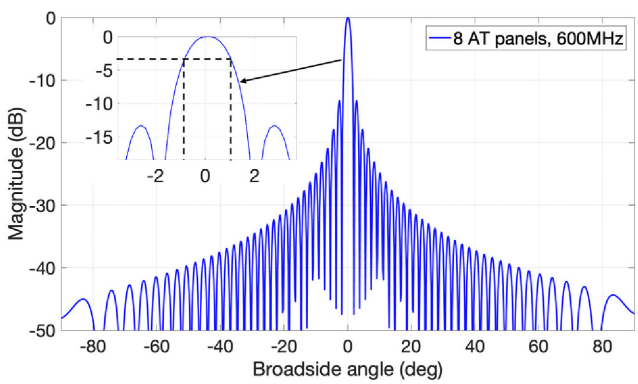

Fig. 6. Simulated VSWR of four AT and four CT subarray panels.

When fully assembled, the beamwidth of the antenna array is approximately 2°, as shown in Fig. 5. The narrow beamwidth is necessary for sounding ice near outlet glaciers where the ice flow is narrow and surrounded by steep walls of rock.

Fig. 6 shows the simulated active voltage standing wave ratio (VSWR) of half of the AT and half of the CT antenna panels because of the symmetry. Panel AT1 represents the AT panel in the front and panel CT1 denotes the CT panel from the left. The locations of subarray panels corresponding to the legends are shown in Fig. 1. The active VSWR of each panel is generally less than 2:1 in the middle band, which is acceptable for radar operation over 600–900 MHz, as the radar waveform amplitude has a 5% Tukey window taper.

III. Fabrication and Measurement Results

As mentioned previously, each antenna subarray panel is fabricated using a panel of rigid foam. Fig. 7 shows the top and bottom of a completed subarray panel and its feed network. The individual monopole elements are affixed to one side of the panel and the cables are routed through the panel to the custom 32:1 Wilkinson power divider (see Fig. 7, right). Once the monopole elements, cables, and power dividers are fixed inside the panel, both sides of the panel are covered with a thin layer of rigid foam and water sealed with a thin layer of fiberglass epoxy resin. The weight of one subarray panel, including the power divider/combiner and jumper cables, is only 9 kg. The total weight of the full array is only 144 kg, which is considered to be lightweight for the 16 m × 17 m antenna array structure.

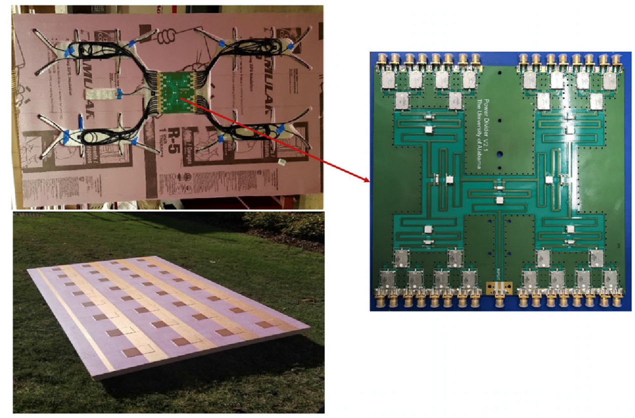

Fig. 7. (Top left) High-power multistage Wilkinson divider is embedded in the foam on the back side of the subarray panel. (Bottom left) Front of the CT subarray panel. The ground of the monopole elements is electrically connected using stripes of copper tape bonded on the foam.

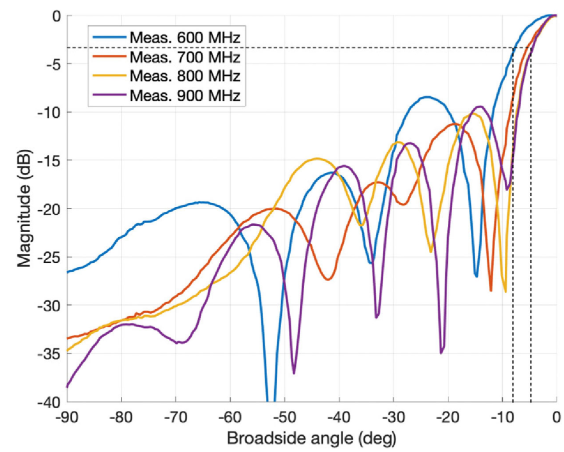

Fig. 8. Measured radiation pattern of one AT subarray panel from 600 to 900 MHz.

After the panels were sealed, one AT subarray panel was measured in the ETS-Lindgren far-field anechoic chamber. The measured radiation patterns over 600–900 MHz are shown in Fig. 8. The overall efficiency of the antenna array including feed network is about 80%. The measured radiation patterns match well with the simulated data except for the slightly higher sidelobes. This could be caused by the insulation material and additional coaxial cables added to the antenna array. From the radiation pattern, the half-power beamwidth is about 16° at 600 MHz and 8° at 900 MHz.

The VSWR was measured for ten subarray panels, including the power divider and interconnect cables inside the panel. The measured results can be seen in Fig. 9. The VSWR remained at acceptable levels over our operating bandwidth. The measurements also show the repeatability of the fabrication process. We have also applied time gating to the measured VSWR to remove contributions from the cables and power dividers. The results are plotted in Fig. 10, which agreed well with the simulated results shown in Fig. 6.

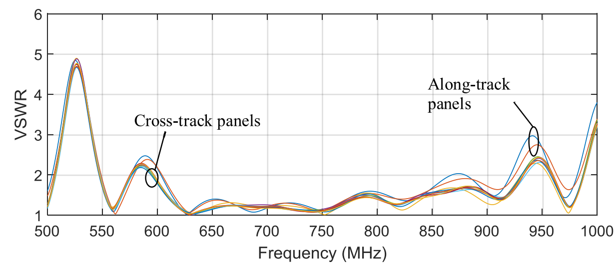

Fig. 9. Measured VSWR of ten antenna subarray panels (with cables assembly and power divider).

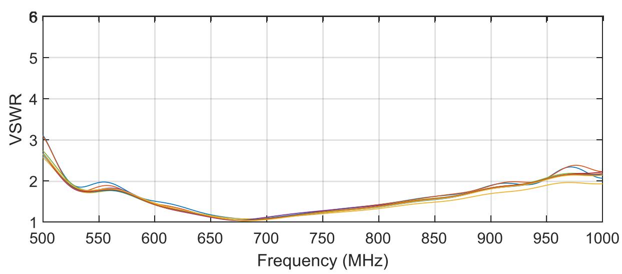

Fig. 10. Time-gated VSWR of ten antenna subarray panels.

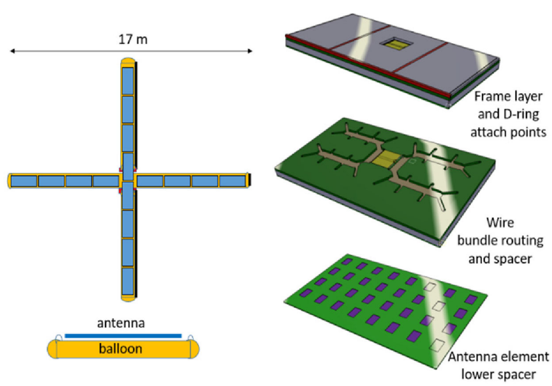

Fig. 11. Diagram of Mills cross panel and assembly of final array. The figure on the right shows the top view of the Mills cross antenna array and the inflatable balloon sledge (yellow) used to tow the antenna array.

Fig. 12. Pistenbully tract vehicle towing Mills cross antenna array.

IV. Field Assembly

When the antenna panels arrived at the East Greenland Ice-Core Project (EGRIP) test site in Greenland [7], we placed the antenna subarray panels on an inflatable balloon sledge for smooth towing on the snow surface. A diagram of the sledge and panel assembly can be seen in Fig. 11. The panels were secured to the sledge with paracord and n-type cables were routed along with the antenna array to the Pistenbully tract vehicle in which the radar system was installed. The antenna array was towed behind the Pistenbully, as seen in Fig. 12. The inflatable sledge is much lighter than a traditional sledge and is approximately 30 cm tall. Such a lightweight and low-profile design makes it feasible to ship and deploy the large antenna to the field. Using the inflatable sledge and individual subarray panels also allows for reconfiguring the antenna array as necessary.

V. Conclusion

An electrically large UHF antenna array with Mills cross configuration developed for polar ice-sounding was discussed in the letter. The modulated antenna array can be easily transported to the polar region without compromising the effective aperture size and high directivity. The ultrawideband performance of circular monopole antenna also meets the high-resolution mapping requierement of ice sounding radar. The antenna array was successfully deployed to EGRIP during the 2018 field season. The lightweight and modular design made assembly and reconfiguration easy to accomplish. The antenna performed excellently and was successfully redeployed to EGRIP in the 2019 field season. Both missions can contribute to the formulation of a satellite mission to completely map Antarctic and Greenland ice sheets, providing the much-needed boundary conditions for ice sheet modeling.

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