AN EHF BACKPLATE DESIGN FOR AIRBORNE ACTIVE PHASED ARRAY ANTENNAS

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ABSTRACT

An array backplate is an essential part of millimeter-wave active phased array antennas. It is the key system that distributes DC, command logic, and EHF signals to the thousands of radiating elements. This paper describes an EHF array backplate design for use in airborne active phased array antennas. The backplate utilizes a multilayer substrate and reduced waveguide for signal routing while a counterflow air cooling technique is used to cool the GaAs MMIC active devices. The integrated design is characterized by temperature coefficient matched materials to insure a rigid, thermally stable structure.

INTRODUCTION

Conformal, active phased arrays have been identified as the antenna technology of the next generation military satellite communication systems. These millimeter-wave arrays will be used for both high performance aircraft and satellite ground terminals. The arrays utilize GaAs monolithic microwave integrated circuits (MMICs) to combine analog phase-shifting, power amplification, and patch radiators within a single chip[1]. While hundreds of MMIC devices are combined and packaged[2] to form the array, the antenna system must also consist of beamsteering computer electronics and a backplate structure. That is, the structure that supports the fragile GaAs subarray chips, cools the chips, and distributes DC, beamsteering commands, and signals to the thousands of patch elements. The array backplate comprises one-third of an active phased array antenna system.

Although much research has been performed in the development of active array MMICs, work in signal distribution techniques must still be addressed. This is a case whereby the device technology has advanced to the point in which the packaging and implementation are lagging far behind.

A backplate structure for a phased array implementation is not a trivial problem. The major emphasis is to simplify the backplate design to reduce cost and improve system reliability.

In this paper we discuss an array backplate design developed for an EHF phased array antenna. The design approach as well as each individual aspect of the structure will be presented.

BACKPLATE ARCHITECTURE

The fundamental approach for the backplate design is to treat the structure as an integrated system. The baseline array building block is a 16-element transmit subarray module as shown in Figure 1. 208 of these modules are cascaded to form the array. Each subarray module employed four GaAs MMIC chips which each contains circular polarization patch elements, analog phase-shifters, and power amplifiers.

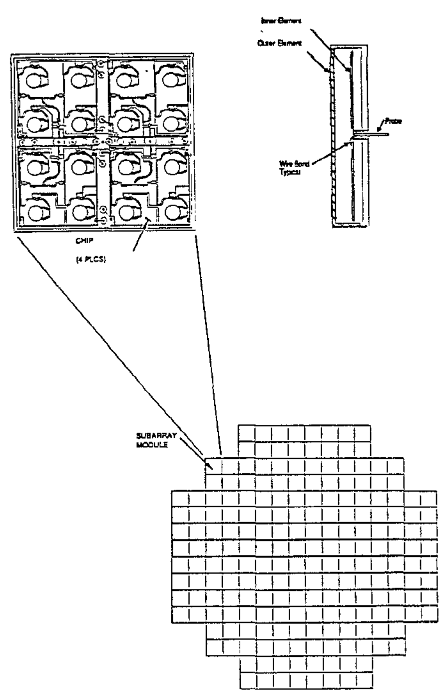

Figure 1 Baseline array configuration is comprised of 208 16-element MMIC subarray modules with single EHF probe for coupling to signal distribution network.

DC POWER AND LOGIC SIGNAL DISTRIBUTION

The integrated array backplate architecture is shown in Figure 2. Subarray modules are formed onto a thick film multilayer substrate which routes DC and logic signals. Thick film is the most applicable approach for an active array with stringent thermal requirements. The substrate has good circuit density as well as excellent thermal and electrical properties. Figure 3 shows a quarter-section layout of subarray modules on a multilayer board.

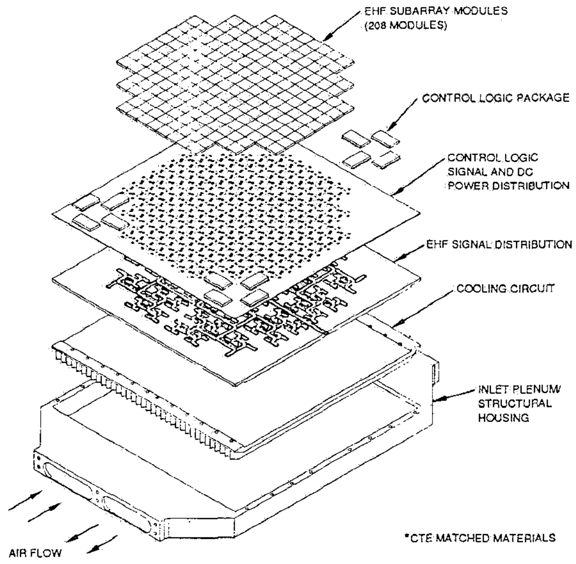

Figure 2 Exploded view of EHF active array antenna with counterflow cooling circuit implementation.

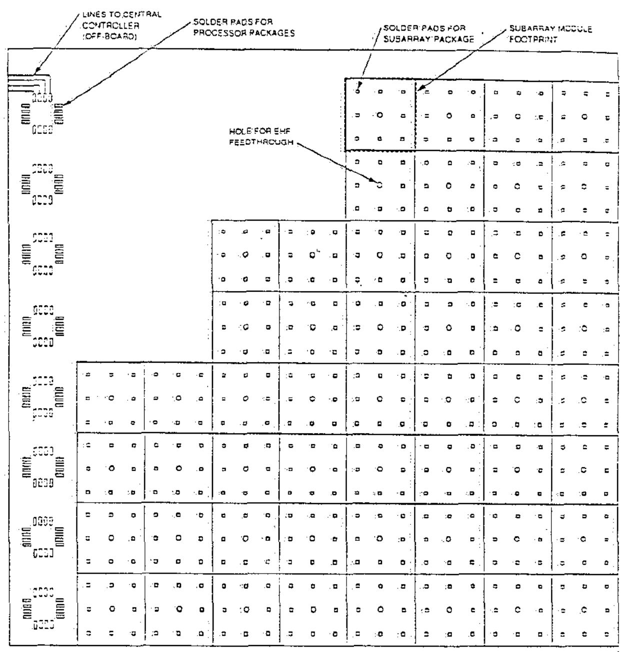

Figure 3 Top layer of DC and logic signal distribution multilayer circuit (one quadrant).

The fabrication process consists of taking a ceramic substrate (typically Alumina or Beryllia) as a base on which to print and fire successive layers of conductors and dielectric material. Each time a layer is applied, the whole structure has to go through a firing process. Dielectric materials are chosen that match the CTE of the array substrate and the other substrate properties. A common dielectric material is DuPont 4575, with a relative dielectric constant of approximately 7, a conductivity of 0.05 W/in degrees C and a CTE of 6.5 ppm/degrees C. Copper metallization is used for the conductive traces of the inner layers and a gold layer is added to the copper on the top layer.

Figure 4 is a cross section of a thick film multilayer substrate showing DC and logic signal lines. All signal layers are separated with ground planes to improve isolation. Vias route the signals between layers and to the MMIC subarray module located on the multilayer surface.

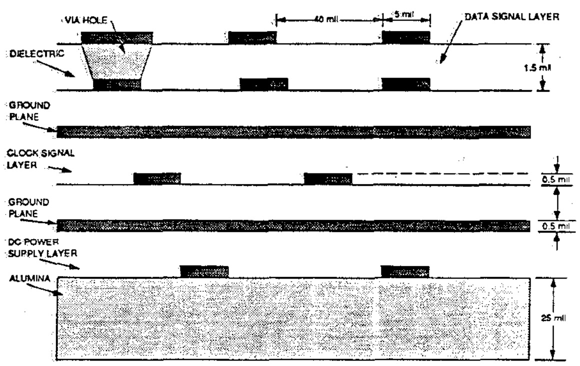

Figure 4 Cross-section of array multilayer distribution circuit.

EHF SIGNAL DISTRIBUTION NETWORK

Although signal distribution can be accomplished with planar substrate or optical techniques, a waveguide approach is desirable in that it is low loss, a good thermal conductor, and is rigid enough to support the MMIC subarray modules.

The feed structure utilizes reduced waveguide. A reduced waveguide corporate feed is an attractive approach to signal distribution because the network is all contained within a single layer. This feed will contain 3dB tees that are cascaded together to form the distribution network. Using standard waveguide, it is impossible to fit all the tees on a single layer. The approach is to reduce this waveguide size to fit all the tees on a single layer and still attain good performance. When reducing the waveguide, the guide must be designed to operate above cutoff so as not to interfere with the operating frequency band.

A 3dB waveguide tee with reduced waveguide dimensions and coaxial probe outputs was fabricated and tested to prove the concept. Experimental data proved that 20dB input return loss can be attained with good power division. This data is shown in Figure 5.

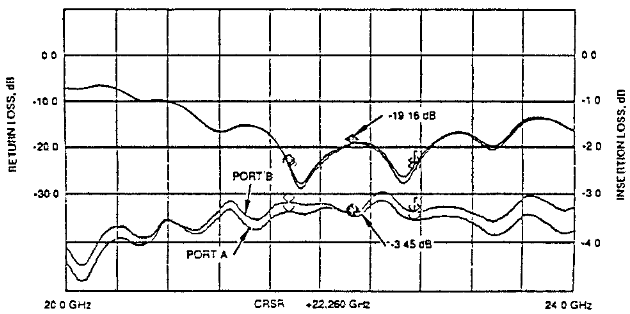

Figure 5 H-plane power divider tee return loss and insertion loss data.

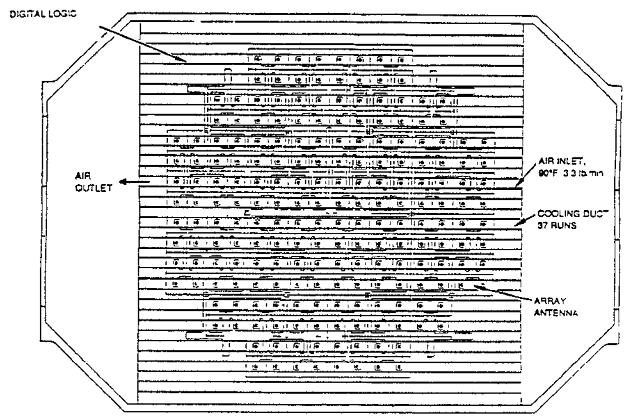

Figure 6 EHF array backplate configuration (top view).

The reduced waveguide is routed through tees to each and every subarray module, the energy being extracted from the waveguide via a transition [3]. This design is characterized by good amplitude and phase balance. The accuracy of the power split is function of the symmetry. The implementation of this design in one layer minimizes the array backplate thickness and facilitates the thermal heat transfer.

An alternative approach is to utilize magic-tee hybrids in place of the basic 3dB tee. This will improve the isolation in the structure. The drawback is that magic tees require a fourth vertical isolation port which is difficult to implement and interferes with the overall mechanical and thermal backplate integration.

THERMAL/MECHANICAL SYSTEM

A counterflow air cooling technique, along with the proper selection of materials (i.e., substrate and waveguide), is the primary architecture to cool the MMIC subarray modules. The flow design utilities existing air flow from the aircraft. The design requires minimal pressure drop and allows better thermal matching of materials.

The thermal design goal for the array is to maintain the MMIC amplifiers at acceptable junction temperatures of 125 degrees C. Reliability of a power amplifier device at 125 degrees C corresponds approximately to 100,000 hours mean time to failure (MTTF). The complete array of 208 elements will dissipate hundereds of watts of power. Because of the tremendous heat problem, the thermal design drives the entire backplate architecture.

The total air mass flow rate used in the analysis was 3.3 lb/min, based on a 4.75 lb/min/kW air flow requirement. The temperature of the inlet air was taken to be 32.2 degrees C(90 degrees F).

The baseline design of the array antenna (Figure 6) utilizes 37 cooling air channels. Each air duct has 3 fins. There are 4 gates per amplifier, 5 amplifiers per chip, 4 chips per subarray module, and 208 subarray modules in the antenna.

The thermal analysis was completed for a counterflow cooling configuration in which the direction of the airflow reverses in alternate ducts. Due to the interaction between the air streams inside the plenums across the separator plate, the plenums were included in the analysis. A cross section of the antenna plenum is included in Figure 7.

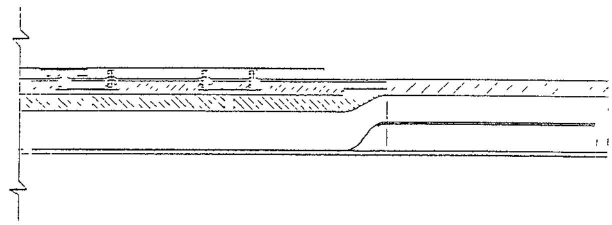

Figure 7 Cross-section of antenna including airflow plenum.

The heat from the amplifier gates in a particular amplifier is dissipated over a small area. From the gates, the heat must travel through a thick layer of GaAs and then through the material layers included in this analysis and shown in Figure 8. The heat is eventually dissipated into the cooling air by means of forced and carried along the cooling air channels until it is exhausted from the exit plenum.

A mathematical model was generated to represent the array antenna and the cooling airflow inside the antenna channels. The model accounts for conduction within and through the various layers of the array antenna as well as forced convection from the antenna channels to the cooling air passing inside them.

The models were analyzed using CINDA (Chysler Improved Numerical Differencing Analyzer). Only steady state was considered in this analysis.

Figure 8 provides the temperature differences in the transverse direction between the layers of the array antenna. The alumina layer exhibits a temperature differential of approximately 7.5 degrees C from center to corner of the antenna. The largest lateral temperature differential in the waveguide/cooling circuit layer is 7 degrees C.

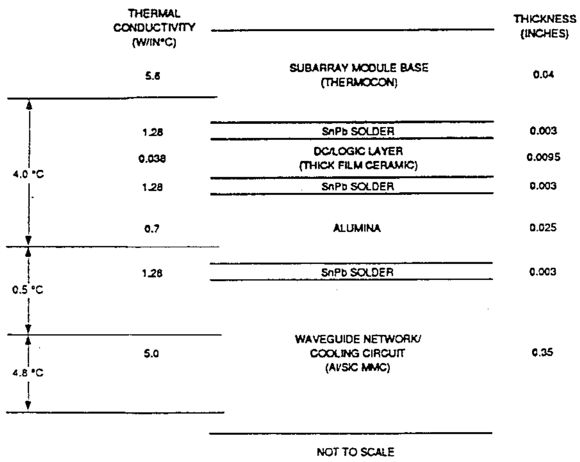

Figure 8 Cross-section of material layers in array antenna.

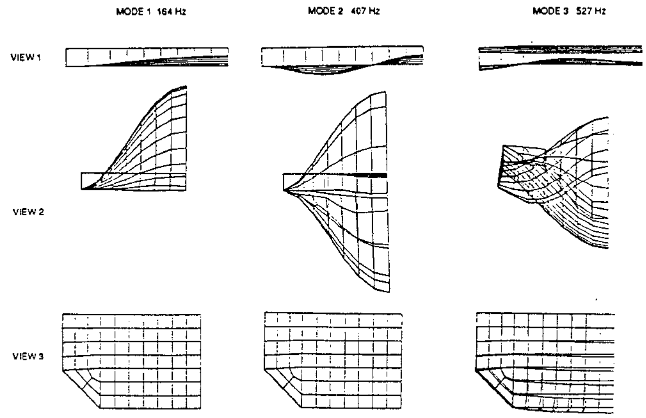

Figure 10 Mode shape.

The temperature difference between the hot and cold amplifier gates is about 5 degrees C. The resulting operating temperature of the hot and cold amplifier gates are 111 degrees C and 105 degrees C, respectively. The total pressure drop across the antenna was determined to be 2.1 inches of water.

The result from this thermal analysis shows that the parallel flow thermal design is sufficient to cool the power amplifiers.

The dynamic characteristic of the antenna with four point hard mounts was evaluated using NASTRAN computer code, a finite element analysis program for stress and dynamics. Due to the symmetry of the structure, only a quarter model is needed to perform the analysis as shown in Figure 9. The mountings on attachments (total 4) are located at pinned ground points. The results for the analysis including model frequency and mode shape are summarized in Figure 10. Due to its high structure stiffness (or high natural frequency), it is very likely that this simple technique of hard-mounting the antenna to the aircraft structure is adequate to withstand the typical low frequency aircraft dynamic environments.

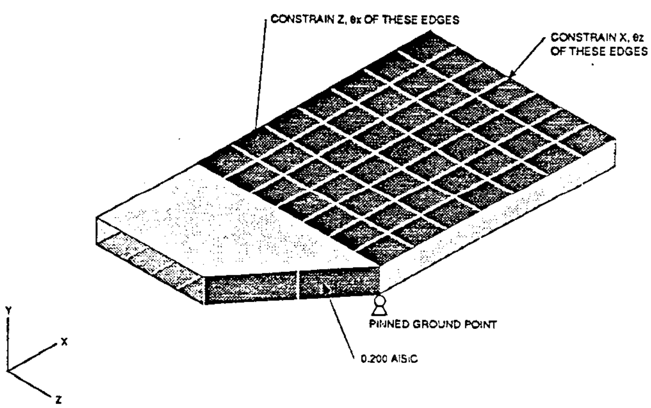

Figure 9 EHF array antenna quarter model boundary condition.

CONCLUSION

A integrated backplate design for millimeter-wave airborne active phased arrays has been presented. The architecture includes a thick film multilayer substrate for DC and logic routing, a reduced waveguide EHF feed network, and a counterflow air cooling circuit. The design is characterized by CTE matched materials to improve thermal and mechanical performance.

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