Advances in Microwave Technology for the MESSENGER Mission to Mercury

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Abstract — **The MESSENGER spacecraft, designed to orbit the planet Mercury, uses the first electronically scanned phased-array antenna for a deep-space telecommunication application. Two lightweight phased arrays, mounted on opposite sides of the spacecraft, provide the high-gain downlink coverage. Medium-gain antennas are used for uplink and downlink during cruise phase. The invention of a method for achieving circular polarization in a high-temperature (+300° C) environment has doubled the science return of the mission relative to the inherent linear polarization from a slotted waveguide array. Monolithic Microwave Integrated Circuits and discrete Heterostructure Field Effect Transistors are integrated to provide the high-efficiency X-band Solid-State Power Amplifier.**

Index Terms — **Microwave power amplifiers, phased arrays, scanning antennas.**

I. INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission launched from Cape Canaveral in August 2004 and began a five-year journey to the planet Mercury. After a nearly seven-year cruise, MESSENGER will be the first spacecraft to achieve orbit about Mercury. The mission includes one Earth flyby, two Venus flybys, and three Mercury flybys before Mercury Orbit Insertion (MOI).

The inner planet trajectory of the MESSENGER mission results in the need for a high-gain downlink to Earth in all directions around the spacecraft. In addition, the extreme thermal environment would cause distortions to the antenna pattern of a traditional parabolic antenna. Phased-array antennas have had limited application in the deep-space community to date, but one-dimensional electronically scanned antennas eliminate the use of deployed components and gimbal dish antennas and offer benefits of high gain, low mass, and graceful degradation. This paper provides a review of the MESSENGER telecommunication system developed by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) with emphasis on the lightweight phased-array and fanbeam antennas and high-efficiency Solid-State Power Amplifiers (SSPAs).

MESSENGER is a three-axis, zero-biased, momentum-controlled spacecraft. The spacecraft uses a fixed thermal shade to maintain the interior of the spacecraft near room temperature. Spacecraft attitude control ensures that the spacecraft is oriented with the Sunshade always facing the Sun. During cruise phase, the spacecraft is oriented with the axis of the solar panels aligned with the ecliptic plane. Once on orbit around Mercury, the spacecraft is rotated about the spacecraft-Sun line to allow viewing of Mercury's surface by the science instruments.

During data downlink periods, the spacecraft is rotated again about the spacecraft-Sun line so that the one-dimensional scanning phased-array antennas can be pointed at the Earth. Two lightweight phased arrays are used for the high-gain downlink. Medium-gain and low-gain antennas are used for uplink and low-gain downlink during cruise phase and emergency.

The MESSENGER telecommunication system is designed to transmit the mission science data, receive spacecraft commands from Earth, and provide high-precision navigation data. As these are spacecraft-critical functions, the architecture for the telecommunication system must be redundant and immune from credible single-point failure. The MESSENGER radio frequency (RF) telecommunication system block diagram uses two Small Deep Space Transponders (SDSTs) cross-strapped to the forward and aft SSPAs.

Within each SSPA are two functional amplifiers, which will be referred to as the distributed and lumped power amplifiers. The distributed power amplifier provides 1.4-W nominal drive level into each of the eight array antenna inputs. The lumped power amplifier provides an 11-W X-band output to the fanbeam antenna and low-gain horn antennas. A set of RF switches following the diplexer allows either receiver or lumped SSPA to be connected with either forward or aft fanbeams or low-gain antennas. This architecture provides cross-strapping for all components except for the distributed power amplifiers which are dedicated to their respective phased-array antennas. The distributed power amplifier provides a graceful degradation in case of an amplifier element failure. Even if a complete array failure occurs, on board solid-state recorders can store the science data for later downlink with the other array.

II. TECHNOLOGY ADVANCEMENTS

To meet the challenges of the mission to Mercury, advanced technology was required in the array and fanbeam antennas as well as the SSPA.

A. Array Antenna

Two lightweight phased arrays, positioned on opposite sides of the spacecraft, are used for the high-gain downlink. Each phased-array antenna is electronically steered over a ± 45° range. One-dimensional steering, in combination with spacecraft rotation, provides antenna coverage for all Sun-Earth-spacecraft angles. Figure 1 shows the coverage area for the array antennas relative to the spacecraft orientation.

The phased-array antenna shown in Figure 2 consists of an array of eight slotted waveguides. The array 3-dB beam widths are roughly 2° in the narrow plane and 12° in the broad plane. The array is scanned in the plane of the broad beam to minimize the number of cables and phase-shifter modules compared with narrow beam scanning. In addition, broad beam scanning results in less pointing loss due to phase errors. Medium-gain (fanbeam) and low-gain antennas are used for uplink and low-gain downlink during cruise phase and emergency. The RF Telecommunication system, including the other antennas, are described elsewhere [1].

Waveguide arrays with slots in the narrow walls are useful for applications involving electrical beam scanning in one plane. However, such arrays are inherently linearly polarized and require additional single or multiple layer structures to achieve circular polarization [2]. The new technique uses short parasitic monopoles mounted to the exterior of the waveguides. The result is a simple, lightweight, and all-metal circularly polarized array capable of operating at high temperatures.

The basic principle of operation is illustrated in Figures 2 and 3. A waveguide cut with a conventional standing wave array of narrow wall slots will excite an exterior electric field with standing wave characteristics. The Ez component normal to the waveguide wall will be in phase with nulls and sign changes halfway between slots. Parasitic monopoles, nominally one-quarter wavelength long, can be strongly excited by this field. Inclination of the monopoles parallel to the y-z plane excites currents radiating an E_y component as well as an E_y component. The E_y component is unwanted in the x-y plane. By using pairs of parasitic elements with the proper spacing relative to the centerline of the waveguide, the unwanted E_y component can be cancelled in the y direction. In the x direction, the array factor will tend to limit this component.

In an array of slotted waveguide "sticks," the gaps between adjacent waveguides can also be excited by the monopoles and radiate as parasitic slots. The depth of these gaps is therefore important, and good distributed electrical contact between the bottom of the waveguides and the ground plane must be established. For the end waveguide sticks in an array, "dummy" waveguides can be used to create gaps on both sides of the active sticks.

Figure 3 shows an idealized model with an infinite ground plane in place. If the current on the parasitic monopoles is in phase with the electric field in the waveguide slots, the y component of the monopole current (J_m) together with its negative image (J_{mi}) will produce a radiated E_y field approximately 90° out-of-phase with the Ex field from the equivalent magnetic current of the waveguide slot (M_s) and its positive image (M_{si}). The currents on the ground plane near the base of a monopole are expected to be nearly in phase with the currents on the monopole. The gap between the waveguides acts like a reactive parallel plate transmission line stub, so the electric field across the gap should be 90° out-of-phase with the ground plane current. The radiated Ey field from the equivalent magnetic current system (M_g, M_{gi}) of the gap is therefore expected to be in phase with the Ey field from the monopole.

To achieve circular polarization, the radiated fields contributed by the combination of the parasitic monopoles and gaps should be equal in magnitude as well as in phase quadrature to that of the slots. The location of the monopoles relative to the slots, the length and slant angle of the monopoles, and the depth of the gaps are all important in establishing this condition. The radiation admittance of the slots is changed by the parasitic elements, so their inclination relative to the waveguide axis must be adjusted to achieve a good input match. The resonant nature of the parasitic elements limits the bandwidth of their operation. However, for a reasonable length standing-wave array, the bandwidth of the series feed remains the limiting factor.

Other examples of the use of wire elements parasitically excited by slots to generate circular polarization include antennas designed for television broadcast [3]-[4]. The techniques for planar arrays of narrow-wall waveguide slots described in this paper have some new features. These include use of the standing-wave nature of the near field and slot-like radiation from the gaps between adjacent sticks.

B. Fanbeam Antenna

The MESSENGER medium-gain antenna produces a "fanbeam" pattern, with 3 dB beamwidths 90° by 7.5°, a peak gain of 15 dBic, and axial ratio better than 3 dB for both the downlink frequency (8.4 GHz) and the uplink frequency (7.2 GHz). Each frequency operates through a separate linear array of short helical antennas fed by a WR112 rectangular waveguide. The uplink and downlink arrays are attached to receive and transmit ports of a waveguide diplexer, respectively, and the common port of the diplexer is fed by a coax-to-waveguide adapter. The short helical antennas for the arrays were designed after Nakano et al. [5], who studied the RF properties of helix antennas of length less than 2λ (where λ is the free space wavelength). Short helix antennas have advantages for this application: a 3-dB beamwidth of 90° and good circular polarization of the radiated field. The arrays of short helix antennas are similar to a linear array also described by Nakano et al. [6] with three notable differences. First, the Nakano array is fed by a waveguide that has a matched load at one end whereas the MESSENGER array waveguides are short-circuited at one end (i.e., traveling-wave antenna versus standing-wave antenna). Second, the Nakano array uses a capacitive button slightly removed from each helix antenna probe to tune out the probe reactance. The MESSENGER arrays use an inductive iris located at the same position as each helix antenna probe. Finally, the materials and assembly method for the MESSENGER arrays are such that the antenna can withstand the harsh environment of the mission.

Aluminum comprises most of the antenna. The array waveguides are designed in two pieces: a broad-wall "lid" assembly that includes the short helix antennas and the remainder of the waveguide that contains the inductive irises. The lid assembly bolts to the remainder section to form a completed array. Incorporated into the helix antennas are glass-bead assemblies similar to commercially available feed-through assemblies. The lid is gold plated and has holes to accept the feed-through attached to each helix. The helix antennas are soldered to the lid using a gold germanium alloy. The arrangement provides an attachment that electrically insulates the helix from the waveguide lid. This attachment was pull-tested and environmentally tested over temperature to ensure that it would withstand the mission environment.

Tuning is accomplished by adjusting the insertion length of the helix probes into the waveguide and by adjusting the width of the inductive iris surrounding each probe. A measurement of antenna return loss is performed on the network analyzer, the probe length is shortened, another return loss measurement is made, the iris widths are widened, and the process repeated until a suitable return loss is obtained at the required frequency. This method of adjusting probe lengths and iris widths in unison ensures that all radiating elements will perform identically. The helix antennas are separated by $\lambda_g/2$ where λ_g is a guide wavelength at the operating frequency. Since this is a standing wave antenna, the electric field at neighboring helix locations is 180° out of phase. In order for the helices to radiate in phase, neighboring helices are rotated about their probe axes by 180° with respect to each other. The uplink array contains 9 helix antennas and the downlink array contains 11 (slightly different) helix antennas.

C. X-Band SSPA

JHU/APL has designed and manufactured a high-efficiency SSPA using a mixture of commercially available Monolithic Microwave Integrated Circuits (MMICs) and discrete Heterostructure Field Effect Transistors (HFETs) for the MESSENGER mission. This mixed integration achieved a similar level of efficiency as the state-of-the-art X-band SSPA using all discrete devices, while at the same time benefiting from the lower component count and increased repeatability and reliability normally associated with an all-MMIC design.

Mission success demands that the SSPA devices have established reliability, usually associated with screened, packaged parts. Although the use of packaged devices with established reliability allows for rapid development and design verification, usually only discrete devices, and MMICs, in die form offered the flexibility to meet simultaneously the efficiency and output power requirements of the SSPA. Figure 5 is a block diagram of the MESSENGER SSPA showing the five MMIC and discrete devices chosen for the design.

To minimize the packaging, fabrication, and screening complexity of the MMIC and discrete devices, a single-chip hybrid approach was chosen. Figure 6 shows the versatile hermetic hybrid package designed by JHU/APL that accommodates each of the five hybrid circuit designs and enables integration of the hybrids into a high-density layout.

The RF power amplifier can consume a significant portion of a spacecraft's primary power. Improvement in power amplifier efficiency translates into the ability either to communicate at higher data rates or to lower primary power requirements and thereby potentially reduce the size and mass of the spacecraft. To obtain the highest efficiency for the MESSENGER SSPA, optimization of the hybrid package parasitics was performed utilizing load-pull and de-embedding techniques. For instance, in the TGA9083 based hybrid, the optimization resulted in the single-output bond-wire arrangement instead of four bond wires recommended by the MMIC manufacturer. This optimization of the bond-wire configuration improved Power Added Efficiency (PAE) by nearly 5% at the nominal drive level of 17 dBm, as shown in the measurements in Figure 7. This seemingly small percentage improvement in efficiency translates to more than 10% of primary power reduction when the overall efficiency of the X-band SSPA is in the 30% range.

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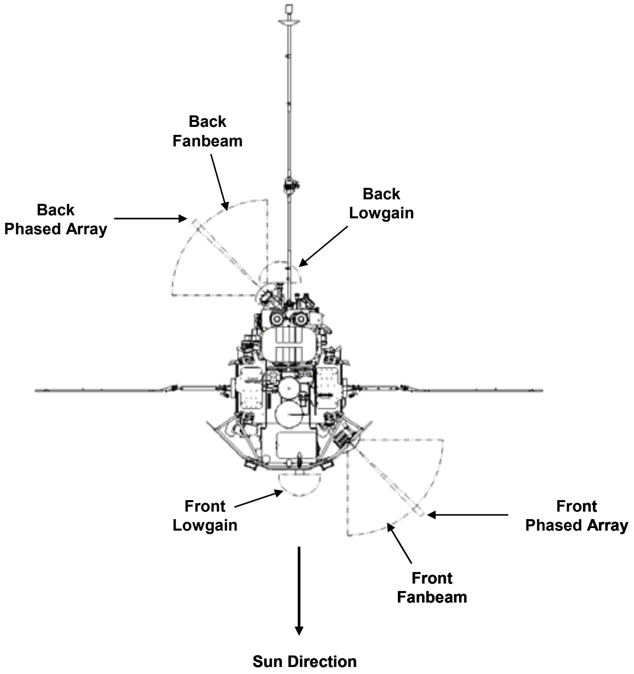

Fig. 1. MESSENGER antenna pattern coverage (top view of spacecraft)

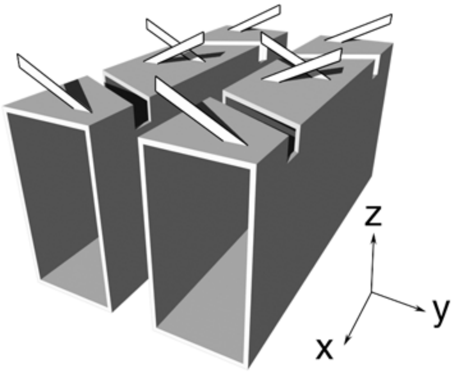

Fig. 2. Array geometry

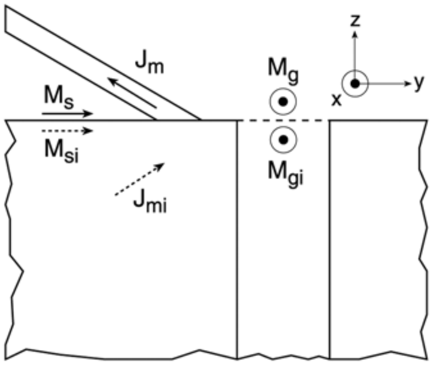

Fig. 3. Currents and fields

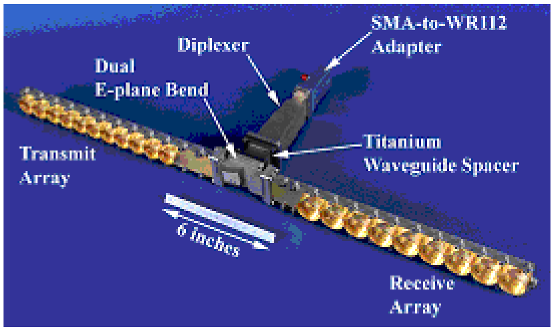

Fig. 4. MESSENGER fanbeam antenna

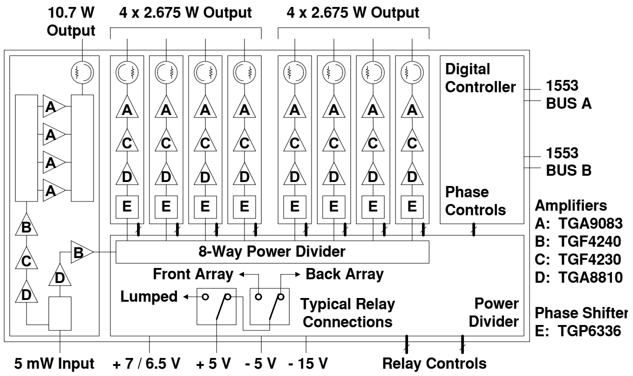

Fig. 5 MESSENGER X-band SSPA block diagram

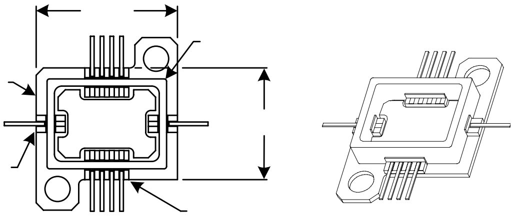

Fig. 6. MESSENGER SSPA common hermetic hybrid package

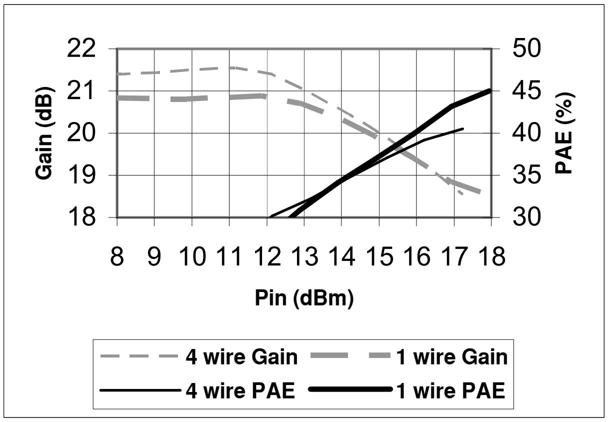

Fig. 7. Gain and PAE versus input power of TGA9083 hybrid with one and four output bond wires.