High-Efficiency High-Power Linearized L-Band SSPA for Navigational Satellites

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***Abstract*— A 400 watt Gallium Nitride (GaN) Solid State Power Amplifier (SSPA) has been developed for use on navigational satellites at L-Band. This amplifier takes advantage of recent advances in high voltage GaN high-electron-mobility transistors (HEMTs), along with predistortion linearization (PDL), to achieve high output power, improved linearity, and greater power added efficiency (PAE). A peak power of 510 W with a PAE of 65.8% has been achieved with a maximum phase slope of less than 1°/dB.**

***Index Terms*— GaN, SSPA, Power Amplifiers, Linearizer, Satellite, L-Band, GPS, Navigational Satellites**

I. Introduction

Navigational satellite systems such as the Global Positioning System (GPS) and Galileo determine location on or near the Earth using radio signals broadcast by a constellation of satellites in different orbits around the planet. These satellites operate primarily at L-Band (1-2 GHz) and on power generated by solar panels. Thus, every watt of electrical power is precious. As a result, the highest possible efficiency is desired from power amplifiers (PAs) used in space applications. These PAs must also satisfy the extremely rigorous reliability demands of space hardware. Because of problems with interference and jamming of space-based navigation signals on the ground, higher power amplifiers are now of interest for the transmission of navigational satellite signals [1,2]. In addition, the development of new modulation techniques is increasing the linearity required from PAs used for navigational application. In this paper an L-band PA designed for space offering 400 watts output power with improved linearity, a phase slope (AM/PM) of less than 1°/dB, and a greater efficiency than previously reported is presented.

The PA brassboard is shown in Fig. 1. The design offers a number of key features: 1) GaN power HEMTs (qualified by the manufacturer to MIL-STD-750 and MIL-STD-883) selected for their high efficiency; 2) predistortion linearization for improved AM/PM performance and superior PAE; 3) commandable saturated output power over a 5 dB range; 4) a common design allowing operation at all L-band navigational satellite frequencies; 5) proven radiation-hardened command & control electronics; and 6) surface-mount assembly architecture.

At L-band, GaN devices are generally more efficient than other materials such as gallium arsenide (GaAs), making GaN an excellent candidate for high efficiency applications. One difficulty in applying GaN devices for linear applications in space is that GaN device linearity is generally not as well behaved as GaAs. This normally reduces the efficiency advantage of GaN, as these devices often need to be operated at greater output power backoff (OPBO) to achieve the required linearity. Linearization allows operation closer to saturation for a given linearity specification, which can significantly increase PAE [3].

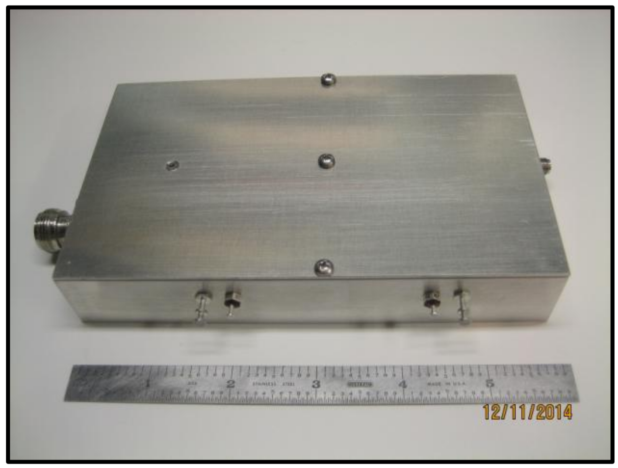

Fig. 1: GaN SSPA Brassboard Assembly

II. Linearization

In order to achieve the highest possible efficiency, a PA must normally be driven as close to saturation as possible. Operating closer to saturation, however, increases distortion, resulting in reduced system linearity. This is the classic linearity - efficiency conflict. This design resolves the conflict by using a linearizer to operate linearly, much closer to saturation.

The PDL generates a magnitude and phase transfer response that is opposite to that introduced by the power amplifier (as illustrated in Fig. 2). To achieve satisfactory wideband performance, a PDL must complement the amplifier's nonlinear characteristics across the band. When combined with a PA, the overall system can have a very high efficiency and the desired linearity. The change in PDL non-linear characteristics over frequency is controlled by selective components in the linearizer and fixed for a given linearizer design.

For a given operating point and linearity specification, linearized amplifiers such as this design have a significant advantage over non linearized PAs. Non linearized PAs must operate at a higher OPBO to achieve the required linearity, while linearized amplifiers operate closer to saturation. In practice, this requires the non-linearized amplifier to be over-sized (higher saturated output power – resulting in larger size, weight and DC power requirements) relative to its desired linear operating point to accommodate for the required OPBO. This results in significant PAE reduction for the non-linearized amplifier.

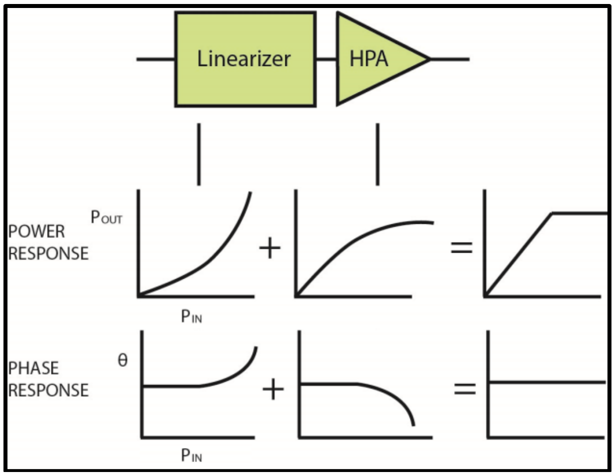

Fig. 2: PDL, PA, and Combined Transfer Response

III. GALLIUM NITRIDE FLIGHT PA DESIGN

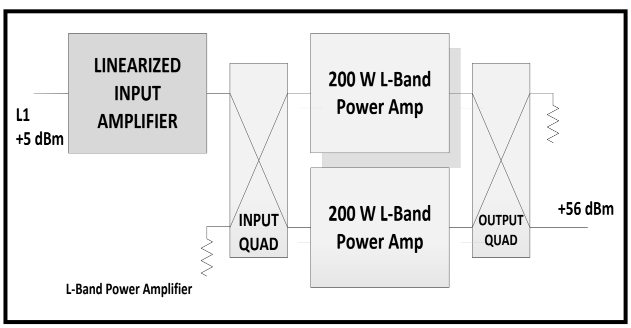

Fig. 3: L-Band 400 W SSPA Architecture

The SSPA reported on in this paper was designed to meet current navigational PA linearity requirements as well as the needs of proposed future systems and modulation schemes requiring much greater linearity. This SSPA was developed specifically for future GPS needs. The design specifications are outlined in Table 1. The SSPA was designed to provide 400 W minimum output power with under a 1°/dB of phase slope (AM/PM) with the highest possible PAE.

A single common design was developed to allow operation at the L1 (1575.42 MHz), L2 (1227.60 MHz), and L5 (1176.45 MHz) GPS frequencies. Sumitomo Electric Device Innovations (SEDI) SGN15H150IV-S GaN power FETs were selected for their high efficiency and power handling capabilities. The SSPA lineup is shown in Fig. 3 and consists of a Linearized Input Amplifier (LIA) and two quadrature-combined > 250 W L-band Power Amplifiers (LPAs). Each LPA in turn consists of a pair of quadrature-combined >100 W GaN power devices. This architecture supports modular construction; each LIA/LPA makes use of a similar housing, construction and FET devices. Only the inter-stage tuning and operating points need to be changed to select different power levels and frequencies (L1, L2, L5, etc).

TABLE 1: 400 W (MIN.) GPS HPA PERFORMANCE GOALS

Specification	Min	Max	Units	Notes
Frequency	1100	1650	MHz	Includes L1, L2 & L5
Linear Power	400	-	watts	At linear oper. point
Efficiency (PAE)	60	-	%	Max power & temp >45% @ 5 dB OPBO
Input Power	5		dBm	
Bandwidth	±50		MHz	
VSWR Input		1.6:1		Z_o = 50 Ohms
VSWR Output		1.43:1		
Gain	53	-	dB	Small signal
Gain Flatness	-	± 0.25	dB	Over operating band
Spurious Signals	-	-80	dBc	Not incl. power supply spurs
AM/PM Distortion		< 1	°/dB	
On-Orbit Life		15	years	
Operating Temperature	0	40	°C	
Group Delay Variation		90	psec	
Radiation (TID)		1500	krad	In conjunction with spacecraft shielding

IV. LINEARIZED INPUT AMPLIFIER

The Linearized Input Amplifier (LIA) provides small signal gain, predistortion linearization, and 40 dBm (10 W) RF drive to the LPA sections. Fig. 4 shows the LIA block diagram.

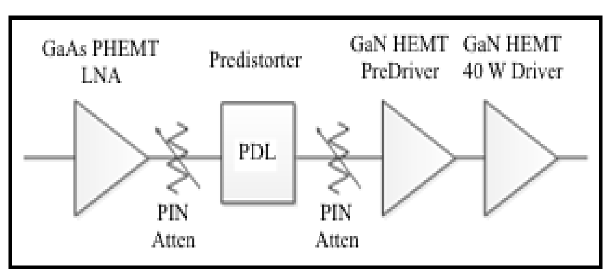

Fig. 4: Block Diagram Showing LIA Functions

The LIA output stage provides a small signal gain of 19.6 dB with a gain flatness of 0.15 dB. It achieves an output power level of +46 dBm (40 W) at a PAE near 55 %. The linearizer stage employs active FET technology with an extensive flight heritage. Two variable attenuators are necessary to adjust the level into and out of the linearizer stage to compensate for variations in temperature and operating point. These are built from flight-proven, glass body hermetic, metallurgically bonded Si PIN diodes. PIN diode attenuator stages provide flat amplitude and phase response over a broad range of attenuation levels and temperature, and are ideally suited for this application.

Though other choices are available from a number of suppliers, SEDI devices were chosen for use in the PA. SEDI has provided thousands of flight devices with substantial reliability and a quality heritage. Also, there can be significant cost advantages in obtaining all the RF devices from the same supplier. The input amplifier stages use SEDI GaAs devices.

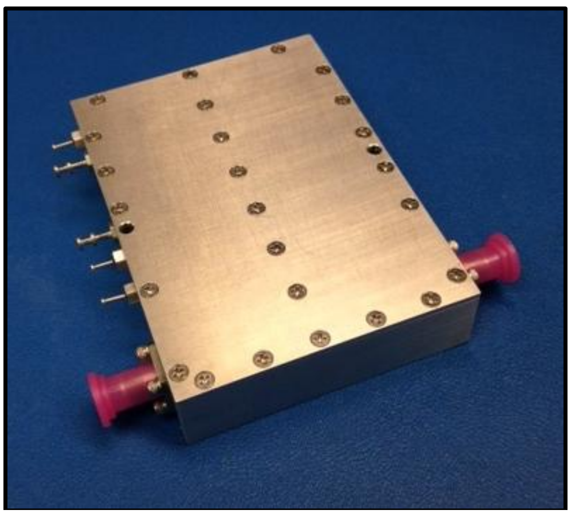

Fig. 5: Linearized Input Amplifier

These low power stages have minimal effect on efficiency, and were chosen due to the lower cost of GaAs compared to that of GaN. The pre-driver and driver stages use SEDI GaN devices. The specific choice of device was made based upon overall efficiency and required drive levels. Fig. 5 shows a picture of the prototype LIA. The devices are input- and output- matched using low-loss transmission line reactive matching techniques.

V. 400 W HPA Output Power Stages

Fig. 1 showed the assembled L1 400 W brassboard. The unit consists of four 150 W devices combined to produce up to 500 W of RF output power. The input to the devices is split four ways, and their outputs combined, using three quadrature stripline hybrid combiners. The same design is used for both the input and output hybrids. The devices are matched to the quadrature hybrids using low-loss transmission line reactive matching techniques. The unit was tuned for flat response over the 1.55 - 1.6 GHz L1 GPS frequency band.

For present GPS SSPAs, the key linearity metric is the AM/PM conversion. Without linearization, the SSPA's phase slope was greater than 2.5º/dB. Fig. 6 shows the transfer response achieved with linearization. When the linearizer was added to the system, the phase slope was reduced to 0.6º/dB, well below the design goal. The linearizer also reduced the compression at SSPA saturation from about 4 dB to 2.5 dB.

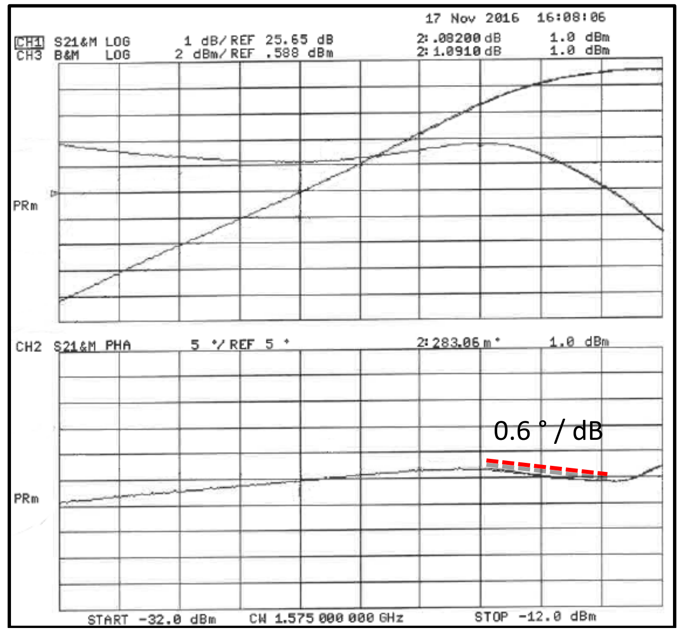

Fig. 6: AM/AM, Output Power, and AM/PM of 400 W Linearized SSPA

Fig. 7 shows a plot of the RF output power and PAE vs. input power, at 40°C, at three frequencies. This data shows that the PAE of the 400 W SSPA is greater than 65% at 400 W, which well exceeds the design goal of the program.

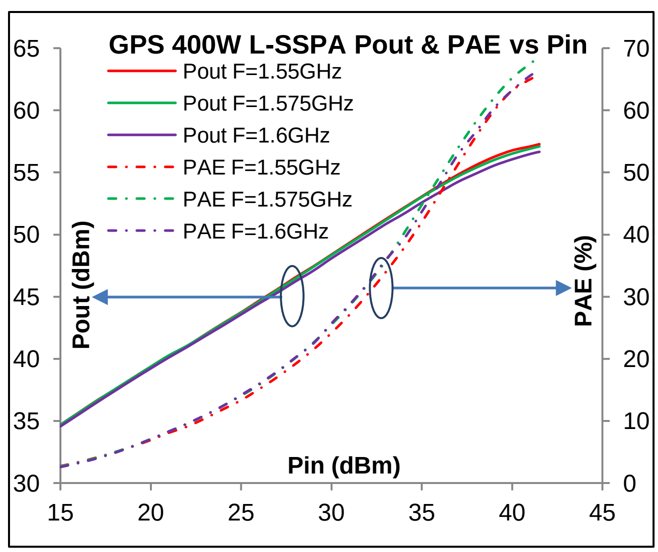

Fig. 7: L1 400 W Linearized SSPA - Pout and PAE vs Pin

Group delay variation vs. temperature is a critical parameter for navigational satellites. The group delay variation of the amplifier could be no greater than 120 ps/5°C, with a goal of 90 ps/5°C or less. Fig. 8 shows that the 400 W SSPA significantly exceeds the required performance.

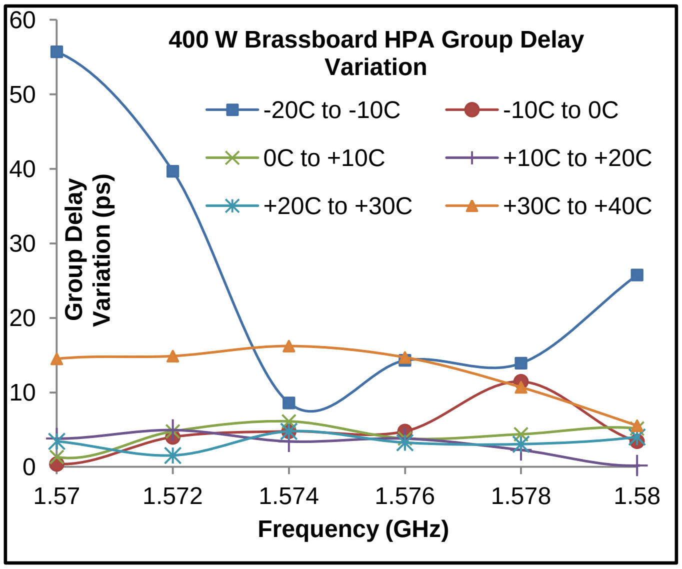

Fig. 8: Group Delay Variation Across ±10°C vs. Frequency

VI. Mechanical and Thermal Design

Proper thermal management is critical to maintaining acceptable device junction temperatures for reliable operation, while meeting the satellite's operational requirements for thermal power dissipation and thermal flux density. Advanced thermal management techniques are used in the design of the LPA housing in order to provide the necessary spreading of high density heat flux away from the GaN FETs, while maintaining an acceptable junction temperature.

VII. GaN SSPA vs. TWTA in Space

In the past traveling wave tube amplifiers (TWTAs) have been used almost exclusively for satellite high power microwave amplifiers. TWTAs generally offered higher power and efficiency than available SSPAs [4]. However, the advantages of TWTAs increase with frequency. At L-band, GaN SSPAs and TWTAs have comparable efficiencies, but the largest available space qualified TWT is less than 250 W [5,6]. If two TWTs are combined to reach 400 W, the metrics shift decisively to favor SSPAs. Besides providing greater efficiency, the SSPA discussed in this paper would have more than a 3-to-1 advantage in mass and size.

VIII. Conclusion

A highly efficient L-band SSPA using GaN FETs has been developed for use in space. This SSPA is designed for use on a navigational satellite and provides more than 500 W of output power with a PAE of > 65% (not including the power supply). This is the highest reported for a satellite PA of any kind for this band. Its performance shows that the combination of linearization and high-voltage GaN devices can provide both the linearity and very high efficiency needed for future GPS and other navigational satellite requirements.

Acknowledgements

The Air Force Research Labs (AFRL) and the Air Force Center's support, under contract FA9453-15-C-0435, directly contributed to development of this SSPA and is gratefully acknowledged. The contract point of contact for this effort was Kenneth Bole, whose assistance is much appreciated. The authors also wish to thank Eugene Pillar, Jay Darish, Allan Guida, Leonard Wintfeld, Nicholas Donatelli, Amy Russo, Michelle Rybinski, and Teri Ulrich at Linearizer Technology, Inc.

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