Development of High Efficiency and High Linearity Power Amplifiers for Space Applications

Riccardo Danieli, Rocco Giofrè, *Senior Member, IEEE*

***Abstract*—This report summarizes the main outcomes of the work proposal presented to the MTT-S Graduate Student Fellowship program 2014, under the topic "Development of High Efficiency and High Linearity Power Amplifiers for Space Applications". The starting point towards this goal is represented by the use of GaN, High Electron Mobility Transistor (HEMT) technology. The idea is to offer valid alternatives to replace Traveling Wave Tube Amplifiers (TWTAs) in space-borne systems with more compact and reliable solid state power amplifiers (SSPAs). To this purpose, different SSPA design approaches, such as the Doherty architecture (DPA) and the harmonic tuning (HT) strategies, have been investigated. Moreover, digital predistortion techniques have been exploited to enhance efficiency and linearity of the overall transmitter. Several prototypes based on GaN devices have been designed, realized and tested as a proof of concept. Experimental results have shown state-of-art performance such as efficiency levels higher than 70 % with less than 3 dB of gain compression and a limited AM/PM distortion in L- and C-band.**

***Index Terms*—MTT-S Fellowship, Power Amplifier, Space borne, SSPA.**

I. Project Outline

A SATELLITE is a complex system with a huge number of electronic components working in harsh environmental conditions. Thus, robustness and reliability are key characteristics that have to be guarantee to assure the overall success of the mission. Moreover, due to the high cost per kilogram of the payload, space and weight of every subsystems have to be reduced as much as possible to maximize the cost-benefits trade-off of the mission. Therefore, the design of space-borne microwave components is usually the result of a compromise among several aspects. In this context, the power amplifier (PA) represents the most critical block since it heavy affects mass, dc power consumption, thermal and mechanical management. Actually, Traveling Wave Tube Amplifiers (TWTAs) are still the preferred solution in almost every bands due to their relevant RF power capability [1], [2], [3], [4], [5]. On the other hand, TWTAs required very high dc voltages and expensive realization processes to avoid multipaction and corona effects. Moreover, they need large volume and heaviness especially in the lower frequency bands such as L and S. Nowadays, with the development of wide band gap solid-state technologies such as GaN HEMT, Solid State Power Amplifiers (SSPAs) start becoming valid alternatives to replace TWTAs also in satellites requiring very high level of RF power. In fact, GaN technology provides transistors with ten times higher power density as compared to Gallium Arsenide devices. Moreover, GaN technology is characterized by very high breakdown voltage, it is able to work at higher junction temperatures and demonstrates higher radiation tolerance. Such properties make possible the realization of power amplifiers with electric characteristics similar to, or even better than the ones of the TWTAs but with smaller size and mass.

On the other side, power amplifiers for telecommunication payloads are expected to be able to handle modulating signals with high peak-to-average power ratios (PAPRs). These signals imply a large back-off operating condition, dramatically reducing the average efficiency levels attained by using traditional PA solutions. Thus, depending by the signal in use, different PA approaches have to be proposed and deeply investigated.

For payload based on signals with high PAPR, the original idea proposed by W. H. Doherty in the far 1936 [6] seems to be a promising and feasible solution to improve the average efficiency without worsening other features. The Doherty power amplifier (DPA) is based on the idea to modulate the load presented to an active device (vacuum tube in the original paper), namely Main (or Carrier), exploiting the active load concept, by using a second active device, namely Auxiliary (or Peaking). It has demonstrated very interesting performance in terrestrial applications when designed with GaN devices even if some drawbacks are still there. One goal of this project was the investigation and exploitation of the Doherty architecture for the realization of SSPA for space systems.

For payload based on signal with not relevant PAPR, harmonic tuning strategies can represent a valid solution to maximize the saturated output power and efficiency [7], [8]. The investigation and exploitation of the harmonic tuning strategies for the realization of SSPA for space systems was another goal of this project.

Besides the average efficiency, the PA is also the main responsible of the overall linearity performance of the transmitter. However, efficiency and linearity are contrasting features in every PA design. Nowadays, thanks to the presence of a digital section in almost all architectures, digital pre-distortion techniques (DPD) represent a valid solution to improve the efficiency-linearity trade-off of the whole transmitter. The integration of DPD techniques together with Crest Factor Reduction techniques (CFR) to linearize SSPA is another goal of this project [9], [10].

In the following, the most relevant achievements for each research line are briefly summarized.

II. Doherty PA

One of the most relevant drawback of the classical DPA architecture is the limited bandwidth due to the presence

Authors are with the Electronic Engineering Department, University of Roma Tor Vergata, Via del Politecnico 1, 00133, Roma, Italy e-mail: giofr@ing.uniroma2.it

of the quarter-wave transformer used to actuate the active load modulation concept. Consequently, to be useful for the next generation systems, where more and more large bandwidth is foreseen, this limiting factor of the conventional DPA has to be overcome. In this context, we have proposed DPA architectures based on novel output combiner topologies capable to reach fractional bandwidths larger than 83%. In the first attempt, experimental results show 42 dBm output power and 65% peak efficiency with a flat behavior in the 1.7-2.4 GHz frequency band under continuous wave signal. Moreover, 50% average efficiency at 38 dBm average output power with 45 dBc of adjacent channel power ratio has been demonstrated under 5-MHz modulated signal. In the second attempt, with an improved combining structure, experimental results with continuous-wave signals have shown efficiency levels within 83%-45% and within 58%-35% at about 42 dBm and 36 dBm output power, respectively, from 1.05 to 2.55 GHz [11].

III. Harmonic Tuning PA

Harmonic tuning strategies are well known in microwave field. In these approaches, a suitable combination of device input and output harmonic terminations is adopted. Output voltage waveform is shaped to fulfill device physical constraints while assuring a higher fundamental component as compared to a class-A amplifier. As a consequence, improvements on output power, power gain, and efficiency are attained. The control of second-harmonic terminations, both at the input and output device ports, has been applied to the design of a narrow-band hybrid-PA at 1.575 GHz. The amplifier is based on the combination of two GaN power bars of 25.6 mm gate periphery each with 0.5 μm gate length. With 40 V drain voltage and a deep class AB bias (total I_{dc} current of 0.9 A), the PA shows an output power of 50.2 dBm with an efficiency of 72% at 2.5 dB of gain compression [8].

IV. DPD and CFR Techniques

Crest Factor Reduction techniques can be exploited to reduce the amplitudes of less frequently occurring peaks of the signal, and along with DPD techniques it can provide a feasible solution to meet the linearity requirements of the used standard. Recent studies have demonstrated that systems working with CFR and DPD can provide promising solutions to the meet the stringent demands of present and upcoming protocols. However, the potential benefits of the concurrent application of both techniques on the efficiency-linearity trade-off of class AB GaN PA designed exploiting a second harmonic tuning strategy have not yet been demonstrated in literature. We did this in [10] and experimental results have shown the possibility to improve the performance of the PA in terms of efficiency, Adjacent Channel Power Ratio and Error Vector Magnitude.

V. Conclusion

Different PA design approaches, such as the Doherty architecture and the harmonic tuning strategies, have been investigated for the realization of GaN high performing SSPAs. Moreover, to maximize the efficiency-linearity trade-off digital predistortion techniques together with Crest Factor Reduction techniques have been developed and applied to the realized prototypes. Several prototypes based on GaN devices have been designed, realized and tested as a proof of concept.

VI. Career Plans

My near term goal is to finish the Ph.D. program, expected for the end of this year enhancing, as much as possible, my capabilities and knowledge in several microwave engineering fields. For the future, I hope to have the possibility to join either a Company or University where I can continue my research.

VII. IMS Participation

To participate at the IMS 2014 in Tampa was a great experience for me, firstly to visit USA and then to attend this very interesting conference. It was an unique opportunity to meet and discuss research with top researchers and scientists from all over the world.

Acknowledgment

I wish to thank the MTT-S Graduate Fellowship program for the award since it was very helpful for my personal and scientific growth.

References

[1] P. Ehret, et al., L-band TWTAs for navigation satellites, *IEEE Trans. Electron Devices*, vol. 52, no. 5, pp. 679684, May 2005.

[2] W. Wojtasiak, et al. The 100W class A power amplifier for L-band T/R module, in *13th International Conference on Microwaves, Radar and Wireless Communications, MIKON*, 2000, vol. 2, pp. 675 677.

[3] S. Rochette, et al. A high efficiency 140W power amplifier based on a single GaN HEMT device for space applications in L-band, in *7th European Microwave Integrated Circuits Conference (EuMIC)*, 2012, pp. 127130.

[4] A. Maekawa, et al. A 500W Push-Pull AlGaN/GaN HEMT Amplifier for L-Band High Power Application, in *IEEE MTT-S International Microwave Symposium Digest*, 2006, pp. 722 725.

[5] K.-W. Kim, et al. 1kW Solid State Power Amplifier for L-band radar system, in *3rd International Asia-Pacific Conference on Synthetic Aperture Radar (APSAR)*, 2011, pp. 14.

[6] R. Giofrè, et al. Being seventy-five still young: the Doherty Power Amplifier *Microwave Journal* Vol. 55 Number: 4 April 2012, pp. 72-88.

[7] R. Giofrè, et al. An Enhanced Phase Shifted Transmitter based on 2nd HT GaN-PAs with Energy Recovery Circuit, *Proceedings of European Microwave Conference (EuMC)*, 2014, Roma, Italy pp: 1560- 1563.

[8] R. Giofrè, et al., "Design of High Efficiency Power Amplifier Based on GaN Technology for Galileo E1 Band" *Workshop on GaN Technology for Space Applications at European Microwave Conference (EuMW)*, 2014, Roma, Italy.

[9] R. Danieli, et al. Low cost AM/AM and AM/PM characterizazion setup based on scalar mesurements, *Proceedings of the European Microwave Integrated Circuits Conference,* EuMIC 2013, Nuremberg, Germany, Oct. 2013, pp. 396-399.

[10] D. Maroor Vikraman, et al. Effects of Windowing Based Crest Factor Reduction Technique on Digitally Predistorted PAs for Multicarrier WCDMA *Accepted for publication in Proceedings of int. wireless symposium*, Shenzen, China, March 30-April 1, 2015.

[11] R. Giofrè, et al., A Closed-Form Design Technique for Ultra-Wideband Doherty Power Amplifiers *IEEE Transactions on Microwave Theory and Techniques,* Vol. 62, N. 12, Dic. 2014, pp. 3414-3424.