Design of an Ultra-High Efficiency GaN High-Power Amplifier for SAR Remote Sensing

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Keywords: GaN Power Amplifier, Active Load-pull, Harmonic tuning

Abstract

This work describes the development of a high-power amplifier for use with a remote sensing SAR system. The amplifier is intended to meet the requirements for the SweepSAR technique for use in the proposed DESDynI SAR instrument. In order to optimize the amplifier design, active load-pull technique is employed to provide harmonic tuning to provide efficiency improvements. In addition, some of the techniques to overcome the challenges of load-pulling high power devices are presented. The design amplifier was measured to have 49 dBm of output power with 75% PAE, which is suitable to meet the proposed system requirements.

1 Introduction

Requirements for next generation SAR remote sensing systems demand new technology to allow these systems to be feasible. Increased swath size, high resolution, rapid global coverage, as well as sub-cm interferometry and polarimetry require advanced techniques such as SweepSAR, which would be employed by the proposed Earth Radar Mission's (ERM) DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) SAR Instrument (DSI). SweepSAR would use multiple transmit/receive channels and digital beamforming to achieving simultaneously high resolution and large swath [1].

The SweepSAR technique (Fig. 1) would use a large aperture reflector with a linear patch feed array, with each set of patches fed by a single T/R module. On transmit, all T/R modules would be used in unison, sub-illuminating the reflector creating a large swath on the ground. While on receive, individual beams would be formed by stitching multiple receivers together using digital beamforming [2]. This technique would produce, for transmit, an electrically small antenna, illuminating a large area on the ground, while on receive, smaller beams would be formed, yielding higher resolution. Due to the large swath, a receiver would have valid data across many transmit events, therefore, any transmit event would actually causes a loss of science data (gaps in the swath). Therefore, the transmit pulse width should be narrow as possible, limiting the total amount of power available to illuminated the ground. However, due to the size of the swath, the transmit energy would be spread over a large area, which would demand a longer pulse width and higher transmit power. A longer pulse width is not an option, therefore, multiple high-power T/R modules would be required.

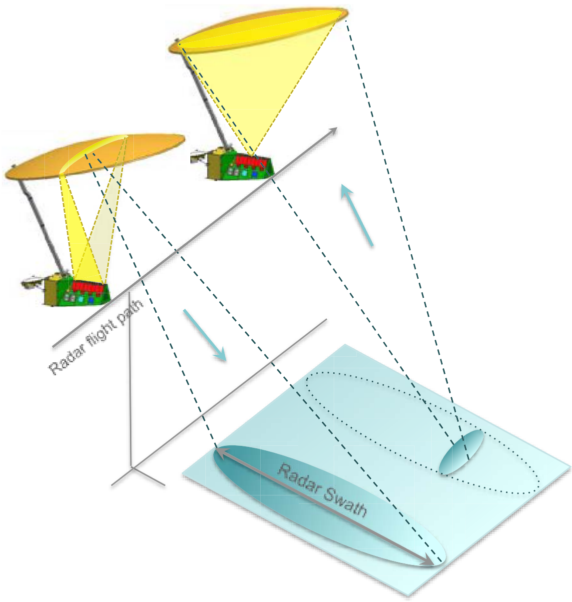

Figure 1: SweepSAR technique highlighting transmit and receive operation. Beamforming on transmit would produce a single large beam covering a wide-swath. Digital beamforming on receive would allow for multiple high resolution beams.

Previous generations of high-power amplifiers utilized GaAs and Si Bipolar transistors and are not suitable for large arrays containing multiple high-power amplifiers. However, Galium Nitride (GaN) High Electron mobility transistors (HEMTs) are an emerging technology that offers high-power density as well as high efficiency, which would make them an effective solution for SweepSAR applications. The high breakdown voltage of GaN as well as it's excellent thermal properties make it a perfect candidate for high-power amplifiers [3]. For commercial applications, GaN has begun to become the technology of choice for RF transmitters.

This work explores the design of a high-power GaN amplifier that is designed using a mixed-signal active load-pull system (MSALPS). The MSALPS allows for an optimized design through the use of harmonic tuning to determine op-

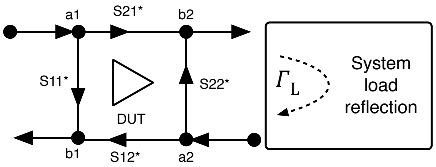

Figure 2: Signal flow diagram for a large-signal load-pull measurement system.

timal impedance points. Section 2 provides a detailed discussion of the mixed-signal active load-pull system, section 3 discusses the details of performing a load-pull on a high power device, and section 4 highlights the final amplifier design.

2 Mixed-Signal Active Load-pull Measurement

A "load-pull" is performed to characterize devices under large signal conditions, where simple linear two-port network theory is not valid. Load-pulling presents the device with desired impedances and measures the large signal response (output power, efficiency, etc) as shown in Fig. 2. Typical load-pull system use mechanical tuners to present a mismatch to the device output, which can be calibrated to create a desired impedance at the device. Mechanical tuners are limited to tuning a narrow band signal as well as in the amount of reflection and therefore impedances that can be achieved at the device.

A solution to the problems with mechanical tuners is the use of active load-pull. This technique uses amplifiers in tuning loops to inject signals back into the DUT, allowing for higher gammas. Active load-pull systems can either be closed or open loop as shown in Fig. 3 [4]. The closed-loop method, Fig. 3a, injects a sampled output signal back into the DUT with appropriate phase and amplitude to produce the desired reflection. This method optimal for fast device characterization, but can be prone to oscillations and requiring filtering. The MSALPS that is discussed in this work is an open-loop active system (Fig. 3b), that utilizes independent arbitrary waveform generators to create independent channels for source and load fundamentals and harmonics. The added complexity of this system allows for improved performance and greater ability to optimize the performance of the device under test.

Anteverta-mw in partnership with Maury Microwave have developed an open-loop active load-pull system that allows for wide-band modulated signals to be characterized. The system contains a National Instrument PXI chassis, which allows rapid and synchronous sampling of the incident and reflected waves as shown in Fig. 4. Each tuning loop requires a separate digital AWG that generates the appropriate waveforms and is unconverted to RF for injection into the device. This procedure is handled automatically through the software and algorithms developed by Anteverta-mw. The directional couplers are used to measure the a and b waves from the input and output and digitized for software analysis. A diplexer is used to power combine the funda-

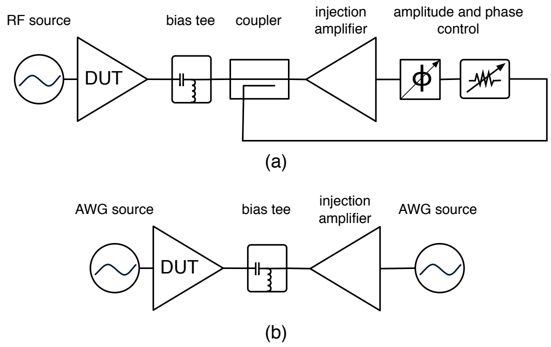

Figure 3: Closed (a) and open (b) active load pull system configurations. In (a) for the closed loop case, the injected signal is a sampled version of the output signal while in the open loop case (b) the injected signal is generated by an independent source.

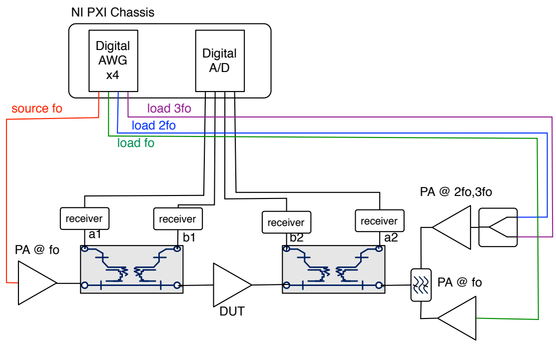

Figure 4: Block diagram of mixed-signal active load-pull system (MSALPS). The system is configured for four tuning loops, the fundamental source, and load fundamental, second, and third harmonics. Each of the loops require an individual arbitrary waveform generator that produces the appropriate waveform to inject into the device to produce the desired Γ.

mental and harmonic signals for injection into the device. Tuning loop A is used for the fundamental source, while tuning loops B, C, and D are used for the load fundamental, second, and third harmonic respectively.

The measurement is performed in two steps. The first step is to determine the proper injection signals for all powers and impedance conditions. As shown in Fig. 5, the injected signals, $a_{1,2}$ are calculated from the reflections to converge to the correct impedance values. Once these waveforms have been determined, a detailed measured is performed for each load and power conditions. The 'real-time' measurement mode allows for rapid characterization by measuring different impedances conditions sequentially during a signal acquisition. Fig. 6 depicts typical waveforms for a real-time measurement using the MSALPS. This technique greatly reduces time needed for load-pull characterization, a typical measurement that could take hours on a traditional passive tuner can take a few minutes on the active load-pull system. Detailed measurement theory of the MSALPS can be found in [5, 6, 7].

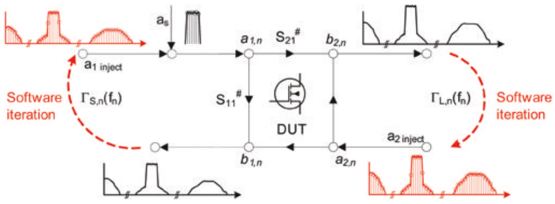

Figure 5: Signal flow graph highlighting software developed injected waveforms to produced desired impedance at device. A_s is the source signal, while $a_{1,2}$ are the injected signals to produce the desired impedance. [Courtesy of Anteverta-mw]

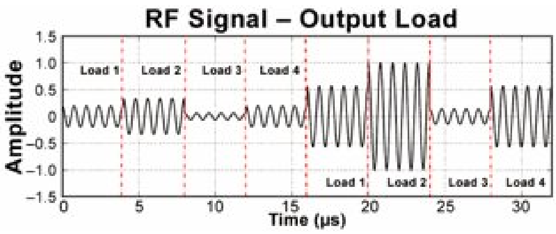

Figure 6: Time series of 'real-time' load-pull waveforms, which allows for rapid characterization of many impedances points. [Courtesy of Anteverta-mw]

3 Load-pulling High Power Transistors

Even though the basic concepts of load-pulling are well understood, it can be challenging to implement these measurements in practice. For high-power devices (over 50 W), it is especially difficult to load-pull such devices due to the very low matching impedances, the high thermal stresses, high dissipated power in the device, and the instabilities that could arise at some impedances during the load-pull.

For active load-pull systems, the injected power required is a function of the DUT's output power and impedance. For very high power devices with low output impedance, it can be challenging to inject enough power into the device from a 50 Ω source to achieve the necessary gamma. The low device impedance causes much of the device power to be reflected and secondly any ohmic losses reduce the power available for tuning. In order to overcome this obstacle, a low-loss, high-power test fixture was developed that transforms the 50 Ω injection amplifier impedance to 10 Ω.

The test fixture is required to be broad band to be able to tune the fundamental, second, and third harmonics to optimize the design. This design uses a Klopenstein (sp) taper that incorporate bias feed network for the gate and drain of the device. Incorporating the bias network allowed for improving the overall loss, maintaining wide bandwidths, and handling the high bias currents and voltages. The feed network consisted of an RF choke and DC blocking cap. In addition, test points were added on the board to monitor the *dc* bias closer to the device to reduce the effects of losses. The test fixture is fully characterized over all desired tuning frequencies, and is deembeded from the measure device performance. Fig. 7 depicts a picture of the fabricated test fixture with a teflon insert that secures the device leads to the board without the need for solder. For this application, the low pulsed duty cycle allowed for simple forced air cooling, however higher average power devices could require inserts that provide for liquid cooling.

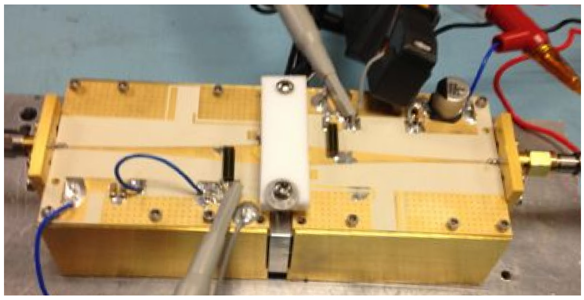

Figure 7: High-power transforming test fixture for MSALPS. Fixture transforms from 50 Ω at the injection amplifiers to 10 Ω at the device reference plane

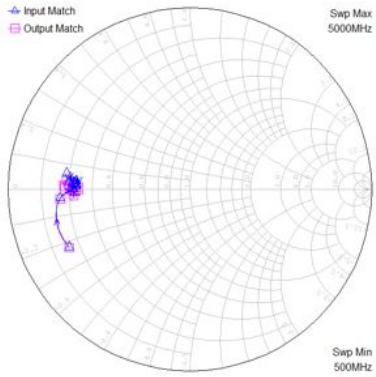

Figure 8: Reflection from DUT reference plane of 10 Ω of input and output transforming test fixture boards. Test fixture exhibits broad band performance from 500 MHz to 5 GHz and less than 1 dB of insertion loss (not shown).

One drawback of the broadband test fixture is that it might increase the chance for oscillations outside the desired injection bandwidth. These devices are typically unstable at low frequency due to their high gain, and therefore care should be taken to avoid causing these low-frequency oscillations. Due to the large currents and voltages, a large amount of power dissipation in the device could occur or large gate voltage swings could damage the gate junction and cause device burnout. Most of these failures cause permanent device damage, and can be observed by high gate leakage currents. In addition, care should to be taken to protect measurement equipment from high-power oscillations that could damage sensitive receive components.

If oscillations with high power devices are observed, a simple reactive feedback network can be added to the DUT to reduce low-frequency gain and improve stability. For this 100 W device measured in this work, a 30 pF capacitor with a 220 Ω series resistor connected with a short wire yielding a few nH of inductance improves the low frequency stability, without impacting performance in the desired frequency band. Fig. 9 shows an image of this feedback network across the device. As shown in Fig. 10, S-parameter response at L-band is unchanged, while low-frequency stability is greatly improved.

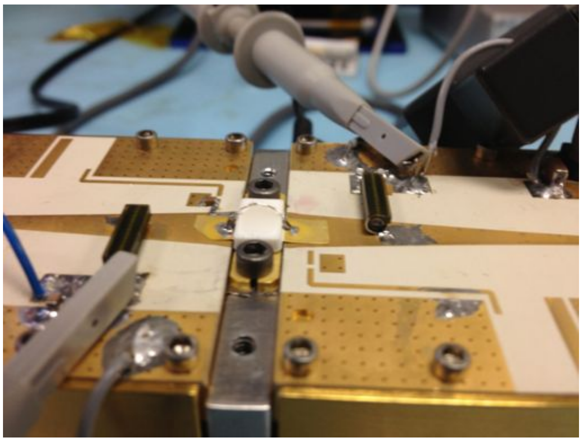

Figure 9: Image of load-pull test fixture with feedback network to improve low-frequency stability. Network includes a 220Ω resistor and a 30 pF capacitor in series.

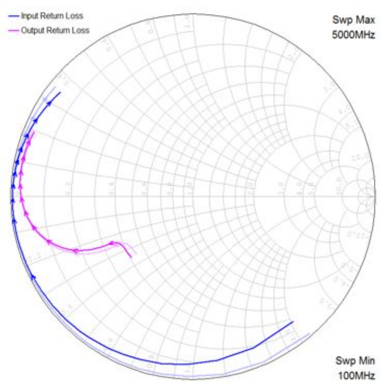

Figure 10: Return loss of simulated amplifier feedback network to improve stability of high power device. Pre-feedback is shown in the shaded lines, amplifier with feedback is shown in the bold lines. Feedback network only had slight in-band changes.

Using the 10 Ω transforming fixture with integrated bias tees and this feedback network, a 100 W GaN HEMT device is characterized on the MSALPS. These measured results are presented in the next section.

4 High power amplifier design

The first step in performing the load-pull characterization is to determine the appropriate input matching condition. Fig. 11 shows the source pull results of the the max transducer gain (G_T) at 1.25 GHz referenced to 10 Ω. The very low input impedance can be difficult to realize and achieve a wide-bandwidth and maintain device stability, a trade-off is made to use a slightly higher impedance, reducing the overall gain. However, the small-signal gain is still high enough for this given application. The source impedance was set to 2.2 - 1.4 j.

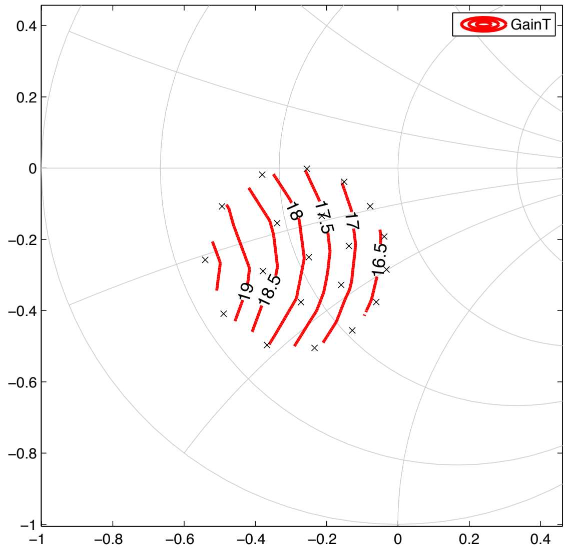

Figure 11: Transducer gain source pull of 100 W GaN HEMT with a 10 Ω reference impedance. Over 19 dB of small-signal gain can be achieved by this device.

The next step was to determine suitable load impedances. Care should be taken to avoid unstable regions of the device during the load-pull. The output power and power-added efficiency (PAE) contours are shown in Fig. 12. The peak output power was measured to be just below 50 dBm, while the efficiency was over 60%. These contours show the tradeoff between output power and PAE. Plotting the power contours for the second and third harmonic (Fig. 13), it is clear that the highest efficiencies coincidence with lower harmonic levels. By controlling the harmonic impedances independently of the load impedance, these contours can be adjusted to achieve high efficiencies while maintaining output power.

Now that source and load impedances are determined, harmonic impedances can be controlled independently to improve efficiencies while maintaining power at the fundamental. Typically, the optimal impedances for the second and third harmonic will be occur at high Γ, so the load-pull can be restricted to a phase sweep around the smith chart. Fig. 14 plots the PAE vs the second harmonic power at 3 dB gain compression for a series of second harmonic load impedances (shown in the inset). Over 70% PAE is achieved with the second harmonic less than 30 dBc with phase angles near $\pi/2$. The same impedance sweep can be performed at the third harmonic, shown in Fig. 15, which increase the efficiency to 72 % and reduce the third harmonic output to less than 36 dBc.

The final designed load-pull amplifier exhibits a total efficiency over 70% with an output power of approximately 49 dBm as shown in Fig. 16, which plots the PAE versus the load output power at the fundamental. The output power is slightly lower than expected, which is most probably due to slight losses in the feedback network. Further design

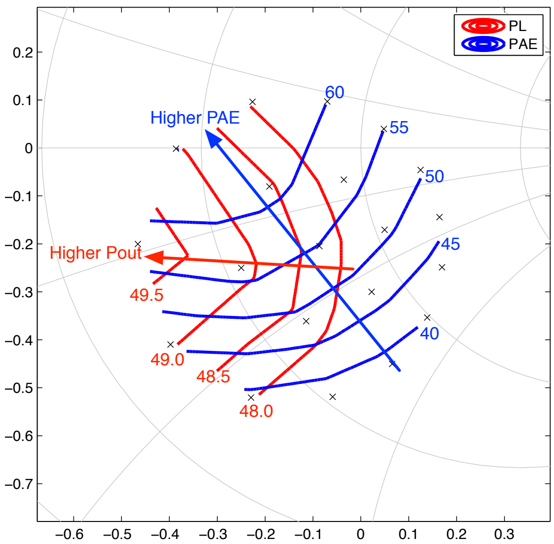

Figure 12: Output power and PAE contours for load-pull result at 1.25 GHz. Output power approaches 50 dBm while peak efficiency is over 60 %.

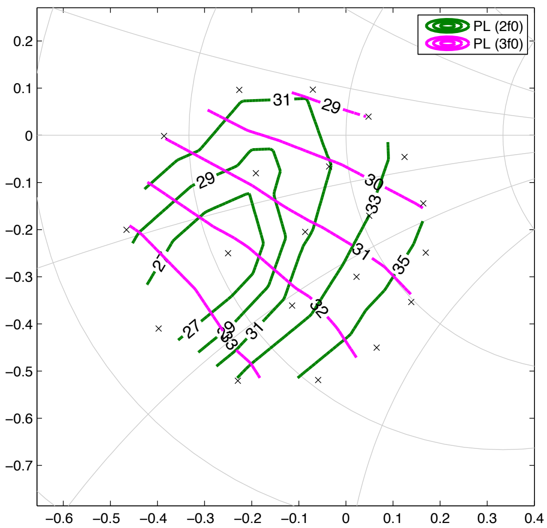

Figure 13: Power contours for second and third harmonic at load. Peak efficiencies correspond to areas of low harmonic content.

optimization can be performed to reduce these losses and enhance performance.

The final step in the amplifier design is the fabrication of the appropriate matching networks. In order to maintain bandwidth, as well as terminate harmonics at the correct impedance, a stepped impedance line with shunt capacitive tuning is used. A depiction of the matching network synthesis is shown in Fig. 17a. and a 3D representation of the matching network board is shown in Fig 17b. The advantage of the stepped impedance line is easily ability to tune the performance to account for parasitics or device variations to optimize performance.

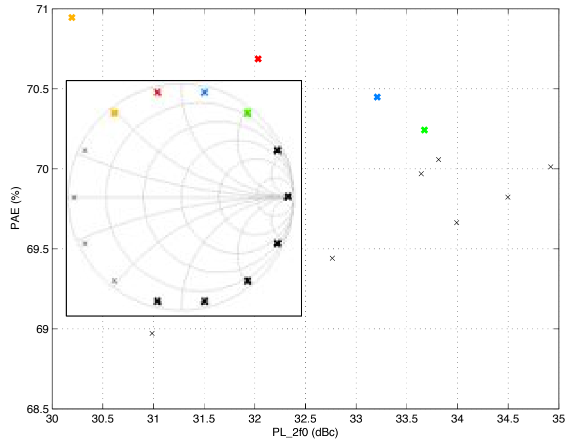

Figure 14: Efficiency as a function of second harmonic power in dBc for swept second harmonic terminations at 3 dB gain compression.

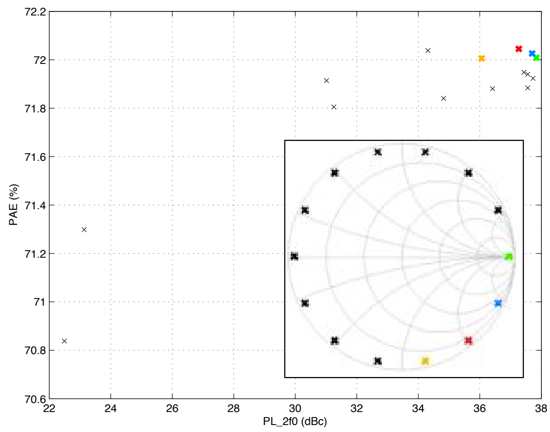

Figure 15: Efficiency as a function of third harmonic power in dBc for swept third harmonic terminations at 3 dB gain compression.

5 Summary

This work presents the characterization and design of a 100 W GaN power amplifier for advanced SAR T/R modules. Such advanced SAR systems utilize new techniques such as SweepSAR that demand high performance transmitters. Such techniques would use sophisticated beamforming to achieve wide swaths and high resolution imagery, but would place strict requirements on the RF hardware. Previous power amplifier technologies would not suit the needs for high peak power and efficiencies. GaN HEMT's for space-based radars allow for improve performance by offering high breakdown, better thermal performance, as well as high power density performance.

In order to optimize the design of these GaN power amplifiers, a mixed-signal active load-pull system is employed to perform large-signal harmonic tuning. Techniques to perform such high-power device characterization is discussed, highlighting the challenging of high power device load-pull. This system allows for sophisticated device characterization and is able to achieve 49 dBm output power with

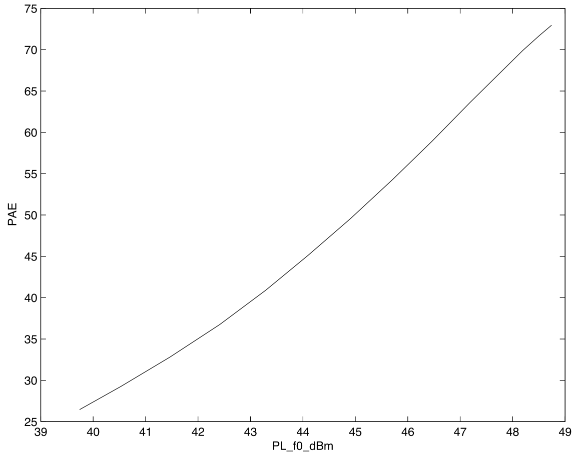

Figure 16: Measured PAE as a function of fundamental load output power for high power amplifier design. PAE is over 70 % with an output power approaching 49 dBm.

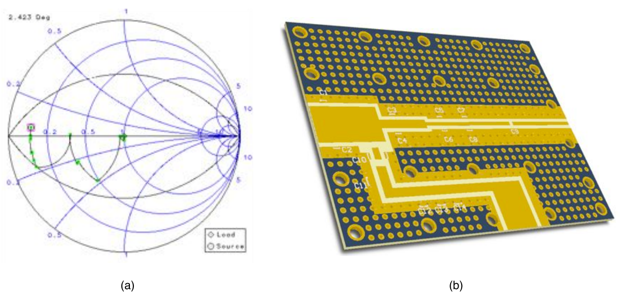

Figure 17: (a) Matching network synthesis of stepped impedance transformer and (b) model of matching network board

almost 75 % efficiency. Future work aims to characterize instantaneous bandwidth performance of the typical RF chirp signal as well as further characterization of dynamic voltage and current waveforms to better understand device reliability.

Acknowledgment

This work is supported by the NASA Earth Radar Mission task at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. ©2012 California Institute of Technology. Government sponsorship acknowledged.

References

[1] P. Rosen, H. Eisen, Y. Shen, S. Hensley, S. Shaffer, L. Veilleux, R. Dubayah, K. Ranson, A. Dress, J. Blair, S. Luthcke, B. Hager, and I. Joughin, "The proposed DESDynI mission - from science to implementation," in *IEEE Radar Conference*, pp. 1129 –1131, May 2011.

[2] A. Freeman, G. Krieger, P. Rosen, M. Younis, W. Johnson, S. Huber, R. Jordan, and A. Moreira, "Sweepsar: Beam-forming on receive using a reflector-phased array feed combination for spaceborne sar," in *Radar Conference, 2009 IEEE*, pp. 1 –9, may 2009.

[3] J. Hoffman, L. Del Castillo, D. Hunter, and J. Miller, "Robust, rework-able thermal electronic packaging: Applications in high power tr modules for space," *IEEE Aerospace Conference*, 2012.

[4] S. C. Cripps, *RF Power Amplifiers for Wireless Communications, Second Edition (Artech House Microwave Library (Hardcover))*. Norwood, MA, USA: Artech House, Inc., 2006.

[5] M. Marchetti, M. Pelk, K. Buisman, W. Neo, M. Spirito, and L. de Vreede, "Active harmonic load-pull with realistic wideband communications signals," *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, pp. 2979 –2988, Dec. 2008.

[6] M. Squillante, M. Marchetti, M. Spirito, and L. de Vreede, "A mixed-signal approach for high-speed fully controlled multidimensional load-pull parameters sweep," in *ARFTG Microwave Measurement Conference*, pp. 1 –5, june 2009.

[7] M. Marchetti, R. Heeres, M. Squillante, M. Pelk, M. Spirito, and L. de Vreede, "A mixed-signal load-pull system for base-station applications," in *IEEE Radio Frequency Integrated Circuits Symposium*, pp. 491 –494, may 2010.

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James Hoffman is a Senior Engineer in the Radar Technology Development Group at JPL. He received his BSEE from the University of Buffalo, followed by MSEE and PhD from Georgia Tech in planetary remote sensing. He has worked in the design of instruments for remote sensing applications for more than 10 years. In previous technology development tasks, he successfully developed a new low power digital chirp generator, which has been integrated into several radar flight instruments. He has experience designing radar systems for both technology development and space flight hardware development, and is currently the RF lead for the proposed DESDynI radar instrument.