

# DESIGN OF AN ULTRA-EFFICIENT GAN HIGH POWER AMPLIFIER FOR RADAR FRONT-ENDS USING ACTIVE HARMONIC LOAD-PULL

Tushar Thrivikraman, James Hoffman

Jet Propulsion Laboratory, California Institute of Technology  
4800 Oak Grove Dr., Pasadena, CA 91109, USA  
Tushar.Thrivikraman@jpl.nasa.gov

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## Abstract

This work presents a new measurement technique, mixed-signal active harmonic load-pull (MSALP) developed by Anterverta-mw in partnership with Maury Microwave, that allows for wide-band ultra-high efficiency amplifiers to be designed using GaN technology. An overview of the theory behind active load-pull is presented and why load-pull is important for high-power device characterization. In addition, an example procedure is presented that outlines a methodology for amplifier design using this measurement system. Lastly, measured results of a 10W GaN amplifier are presented. This work aims to highlight the benefit of using this sophisticated measurement systems for to optimize amplifier design for real radar waveforms that in turn will simplify implementation of space-based radar systems.

## 1 Introduction

GaN devices are increasingly becoming an enabling technology for advanced space-based radar systems. The use of GaN allows for improved system performance due to its high efficiency and output power. In addition, the adoption of GaN into commercial applications, such as cell phone base stations has allowed the technology to mature and improve reliability and device performance.

Such high priority missions as the proposed Earth Radar Mission's (ERM) DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) SAR Instrument (DSI) utilizing the SweepSAR concept are made feasible by the use of high power, high efficiency solid state power amplifiers [1, 2]. In the design concepts for this mission, multiple high power TRM (transmit/receive modules) (> 100 W output power) that are thermally managed by the surface area of the TRM acting as the thermal radiator. For typical duty cycles and efficiencies, over 20 W of power must be dissipated by this surface, requiring extremely large TRM, which are not suitable for this space borne system.

GaN technology presents two benefits for the proposed DSI: (1) a potential reduction of thermal stresses due to increased efficiency and (2) ability to operate at higher junction temperatures. By easing the thermal requirement, the radiator size may be decreased allowing for a more compact TRM, reducing mission costs. In order to fully op-

imize the high power amplifier design using GaN HEMT technology, the new characterization technique, active harmonic load-pull, is being developed to increase efficiencies and reduce harmonic levels over a wide-band [3]. Though tuning load and harmonic impedances Class-J current and voltage waveforms can be engineered that provide optimal balance between performance, bandwidth, and linear response. There is increasingly more literature on the use of these systems for designing amplifiers for use with modulated telecommunications signals, but to the authors knowledge, no work has been demonstrated this technique for typical radar signals.

This work will present an overview of a wide-band mixed signal active harmonic load-pull system (MSALPS) [4] that is capable of harmonic tuning over a real radar waveform (such as a chirp) to optimize amplifier performance and efficiencies to > 70 %. This system was developed by Anterverta-mw in partnership with Maury Microwave and a detailed discussion of the load-pull system is presented in [5]. Section 1 will provide an overview the theory behind the MSALPS system and the specific measurement setup used for amplifier characterization. Section 2 will present a design overview of an L-band GaN amplifier for use in the proposed DSI TRM with the measured results of this design presented in section 3.

## 2 Mixed-Signal Active Load-pull Measurement Overview

The basic concept of "load-pull" is to present known impedances to devices under test (DUT) in order to determine their characteristic response, enabling performance optimization for non-linear devices. Fig. 1 shows the signal flow graph for a non-linear two-port device where  $a_{1,2}$  represent the incident waves and  $b_{1,2}$  are the reflected waves.  $S_{xx}^*$  represents the large signal s-parameters of the DUT. For a small-signal network analyzer, the DUT is insensitive to load impedance and therefore standard VNA error correction terms can be used to calibrate to the reference plane of the device to extract s-parameters. However, for large signal conditions, load-pull is necessary since the DUT is no longer linear and therefore linear superposition and simple two-port network theory is not valid. Impedance tuners allow a simulated  $\Gamma_L$  presented to the device and enables the measurements of the non-linear large-signal S-parameters.

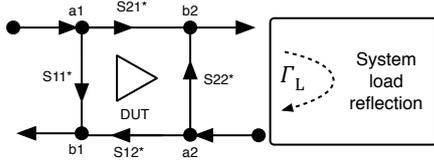


Figure 1: Signal flow diagram for a large-signal load-pull measurement system.

Traditionally, load-pull systems are passive, using mechanical probes to create a mismatch that presents the desired impedance by reflecting signal back to the DUT. These systems have been used for years for amplifier development with modern tuners being electronically controllable and able to tune fundamental and harmonic impedances. Passive systems however are constrained due to tuner and system losses that limit the maximum reflection coefficient achievable. For typical high power devices, output impedances are below  $5 \Omega$ , and therefore are difficult to characterize on passive load-pull systems. Another limitation for wide-band signal are the time-consuming tuner calibrations that are only valid to for single-tones and/or harmonics requiring characterization at different fundamental tones within the frequency band of interest to optimize the amplifier design for wideband operation.

Many of these performance limitations of passive tuner systems can be addressed by active load-pull. As the name suggests, active load-pull is achieved by injecting a signal into the DUT to create the desired impedance. The active injection can be performed by either closed- or open-loop methods. The closed-loop method, Fig. 2a, 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. 2b), that utilizes independent arbitrary waveform generators to create independent channels for source and load fundamentals and harmonics.

An open-loop system requires more signal processing and software iterations since the reflected wave is generated independently from the incident wave. However, the added complexity allows flexibility with the ability to tune wide-band modulated signals and have independent control of harmonics as well as the ability to achieve very high reflection coefficients as they are only limited by the power supplied by the injection amplifier. Fig. 3 shows the MSALPS configured for four tuning loops. Anteverta-mw and Maury Microwave's implementation utilizes a National Instrument PXI chassis, which allows rapid sampling of the incident and reflected waves. 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

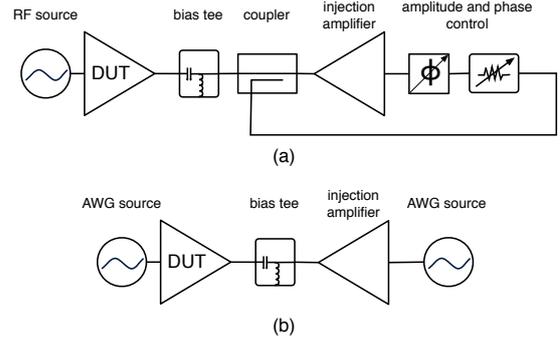


Figure 2: Closed (a) and open (b) active load pull system configurations. In (a) for the closed loop case, the injected signal is a sampled version of the output signal while in the open loop case (b) the injected signal is generated by an independent source.

diplexer is used to power combine the fundamental 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.

For these measurements, the load fundamental, second, and third harmonics are swept to determine optimum impedance. The source fundamental can also be swept with the match condition as close to the small-signal  $S_{11}$  conjugate match for optimum power transfer. In addition, a stable phase reference is used to determine the dynamic I-V characteristics of the device, which can be used to optimize the waveform for Class-J operation and more sophisticated waveform engineering.

The measurement is performed in two steps. The first step is to determine the proper injection signals for all powers and impedance conditions. This step is achieved through the use of the AWGs and adjusting the waveforms on a pulse-by-pulse basis to achieve the necessary powers and impedances at both the source and load fundamentals and harmonics. The second step of the measurement routine these calculated injection signals are used to fully characterize the device with both RF and DC parameters measured. Detailed measurement theory of the MSALPS can be found in [6, 7, 8].

Another important feature of the MSALPS is the ability to load-pull modulated signals that have both frequency and amplitude variation. This allows for very precise amplifier characterization and tuning to optimize the performance for specific radar waveforms. The requirements for the proposed DSI to achieve the desired resolution require chirp bandwidths as wide as 80 MHz at L-band. Designing optimal amplifier performance over this band is extremely challenging with conventional load-pull systems. Fig. 4 is an example linear chirp waveform that can be programmed into the MSALPS system.

### 3 Amplifier Design Overview

This section outlines the basic steps to use the MSALPS to design a highly efficient HPA. The steps are as follows:

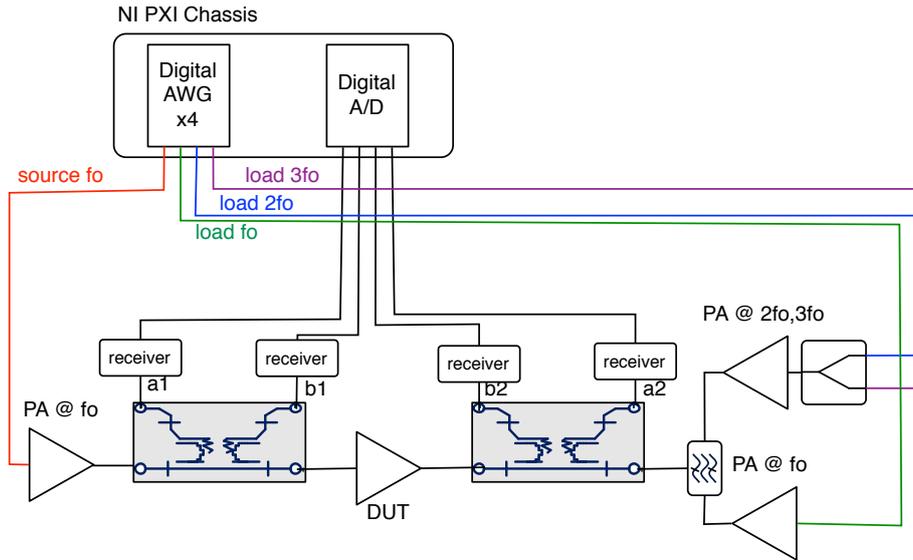


Figure 3: Block diagram of mixed-signal active load-pull system (MSALPS). The system is configured for four tuning loops, the fundamental source, and load fundamental, second, and third harmonics. Each of the loops require an individual arbitrary waveform generator that produces the appropriate waveform to inject into the device to produce the desired  $\Gamma$ .

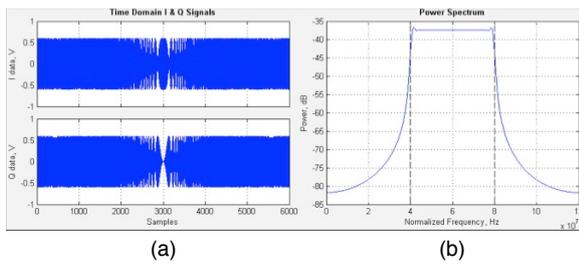


Figure 4: Modulated chirp waveform in the (a) I-Q time and (b) frequency domains. The modulated waveform can be used to synthesize actual expected input waveforms, improving system design fidelity.

1. Perform DC output characteristic sweep to determine appropriate quiescent point of operation. Class-J amplifiers are typically biased near class-B operation.
2. Measure small-signal S-parameters of device to determine input and output matching conditions.
3. Perform fundamental source and load-pull to determine optimal matching regions for given bias points
4. Perform harmonic tuning to adjust second and/or third harmonic to present unmatched conditions at those frequencies

An example load-pull sweep configuration from step 4 is shown in Fig. 5, which shows the impedance points that are used to tune the source fundamental, load fundamental, and load harmonics. The sweep was performed from linear to saturated power at 10 % duty cycle.

For reference, a sample single-tone measurement result is presented in this abstract. Here, a 10 W GaN HEMT device is characterized in a high power test fixture, pictured

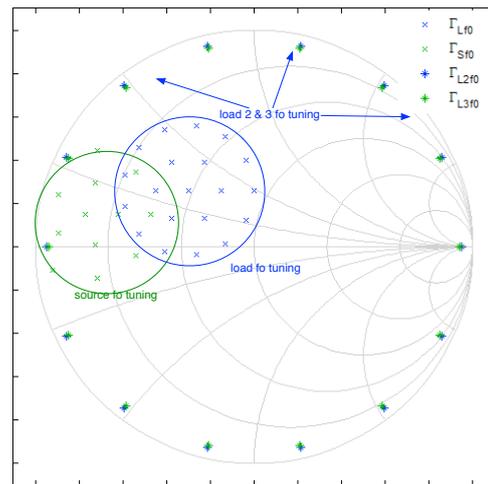


Figure 5: Typical load-pull point constellation for tuning source fundamental, load fundamental, and load harmonics. The source and load fundamental are centered around the small signal conjugate reflection coefficients, while the second harmonic is tuned for maximum reflection.

in Fig. 6 with the bias tees. The device was biased near class B operation since typical high power radar amplifiers are operated in saturation, linearity is not a major concern for radar HPAs. The measurement was calibrated to the device reference plane, but still includes package parasitic losses.

For the initial design, optimal source and load impedances at the fundamental were tuned for the 10 W GaN HEMT device biased in class B operation. The source match was matched to the large-signal  $\Gamma_{in}$  while the output was swept around the small-signal  $S_{22}$  conjugate match. Output power of 40 dBm and 68 % PAE are shown in Fig. 7 without the

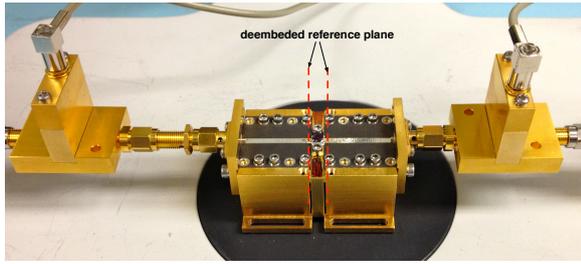


Figure 6: 10W GaN device in test fixture for load-pull showing reference plane with fixture deembedded.

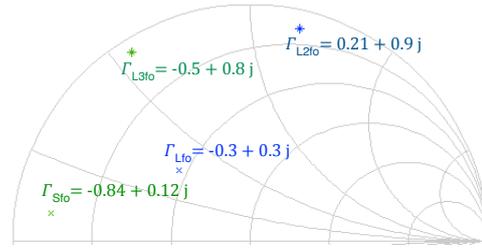


Figure 8: Final optimal matching impedances showing fundamental source, load, and harmonic impedances.

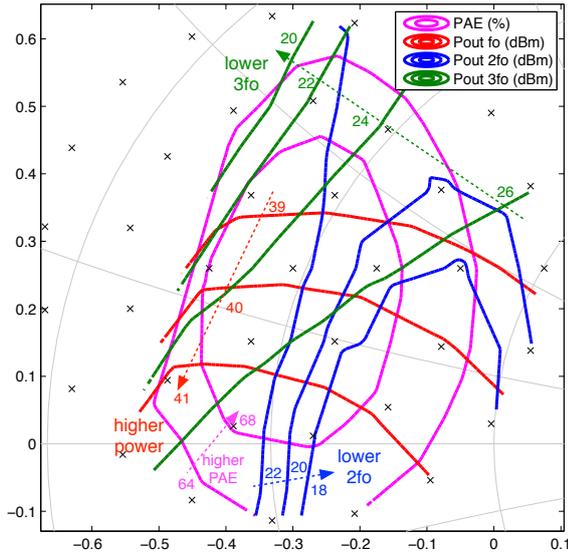


Figure 7: Design of 10W GaN HEMT device in class B operation with no harmonic control. Output power of of 40 dBm approaching 70% PAE are achieved.

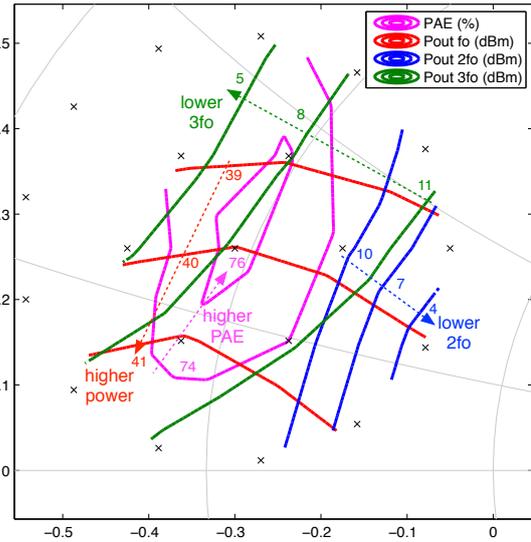


Figure 9: PAE and output power contours for 10W GaN HEMT device with a single tone stimulus. The PAE is shown in magenta, with the fundamental, second, and third harmonic shown in red, blue, and green respectively.

use of active harmonic control. Even though this performance is acceptable, the second and third harmonic components are high ( $>20$  dBm). The contours for PAE and harmonics show a tradeoff between minimizing either second or third harmonic content and optimal efficiency. For example, by choosing a load impedance to reduce the second harmonic, the third harmonic becomes larger, trading off efficiency. Using the MSALPS for harmonic tuning adds the additional control knobs to optimize impedances independently for both the second and third harmonic, thus improving the overall efficiency.

These results can be directly compared to Fig. 9, where the additional two tuning loops of the MSALPS system were used to control the second and third harmonic impedances. In order to achieve maximum efficiency a reflective impedance (open or short) is used.

For this sweep, the source and load second and third harmonic were tuned to optimal points within the given tuning range as presented in Fig. 5, converging on the final impedance matching values shown in Fig. 8. Sweeping the fundamental load, the PAE and power contours are shown in Fig. 9. By controlling the harmonic content, the efficiency can be improved to over 76% while still achieving

over 10 W output power, and reduced harmonic output. The optimal point for PAE still highlights the tradeoff between power at 2fo and 3fo. This technique can also be used to reduce harmonic content to comply with international radio emission guidelines.

To further gain insight of the amplifier characteristics the dynamic I-V waveforms can be calculated using the MSALP software. In order to fully understand the current and voltage waveforms within the device as presented in [9], the package parasitics and internal drain-source capacitance should be deembedded to the internal current generator of the transistor as shown in Fig. 10. Using a commercial simulator tool, the fixture, package, and internal device  $C_{DS}$  were modeled and extracted with the matching impedances translated to the internal device reference plane as shown in Fig. 11.

Understanding this transformation from the package reference plane to internal current generator is important for harmonically tuned amplifiers. The fundamental and harmonic impedances must be controlled over a wide bandwidth to maximize performance. As shown in Fig. 11 the parasitics have a large effect on the matching conditions at the internal generator.

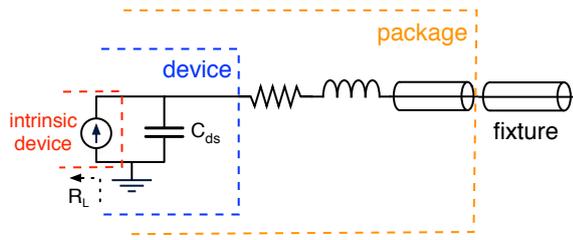


Figure 10: Model of package and device parasitics deembedded to allow measurement of dynamic current and voltage at the intrinsic device current generator.

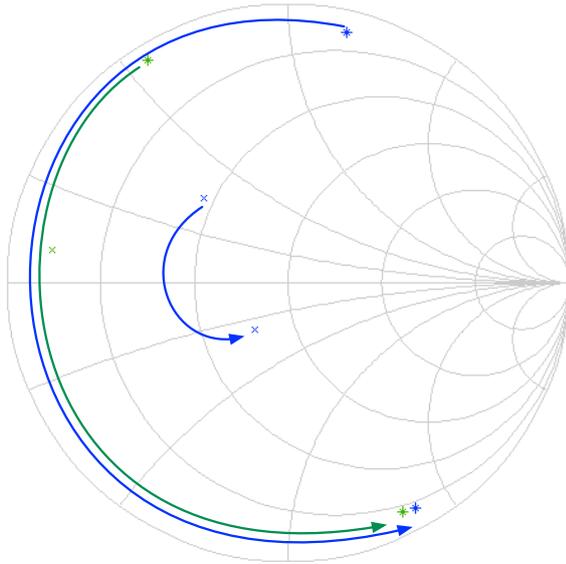


Figure 11: Shifted matching impedances to present to intrinsic device removing effects of package parasitics and drain source capacitance.

Once these parasitics are removed and the impedance points are shifted to the internal generator reference plane, dynamic current and voltage waveforms can be calculated. Fig. 12 plots the current and voltage versus time at 3 dB compression, showing the peak voltage approximately at 55 V, with a peak current of 1.4 A. Fig. 12 plots the complex load line for the matched amplifier. This load line indicates class B like waveforms due to the ideal circular nature of the response. The negative portions of voltage and current waveforms indicate that there are additional parasitics capacitances that were not successfully deembedded, and therefore further optimization of the package model is required.

#### 4 Summary

In summary, this abstract presents an overview of mixed-signal active load pull system that can be used for developing RF front-ends for space-based radars. The load-pull system may be used to improve amplifier efficiencies over a wide-bandwidth, reducing thermal constraints and spacecraft bus requirements for such missions as the proposed DSI.

A 10 W GaN amplifier was designed to achieve over 76 %

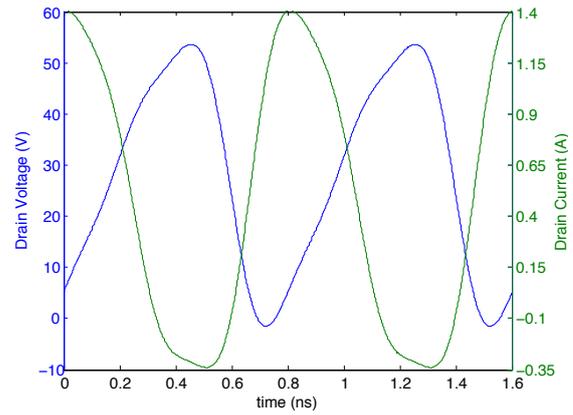


Figure 12: Current and voltage waveform at intrinsic device, showing peak currents and voltages.

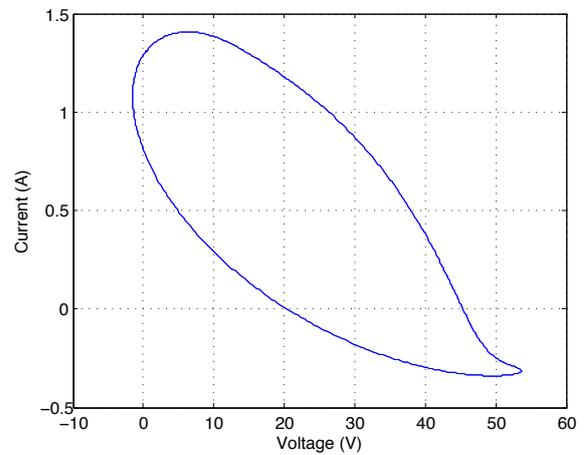


Figure 13: Complex load line for matching amplifier at 3 dB compression.

efficiency by optimizing the harmonic content. In addition, dynamic current and voltage waveforms were calculated at the intrinsic device current generator by removed packaging effects and drain source capacitance. The purpose of this work is to highlight the general procedure and achievable performance of developing high power GaN amplifiers using this technique and the benefit to the instrument design through optimization. Future work includes developing matching networks to achieve these impedances as well as characterize the amplifier using a modulated response.

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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.

**Tushar Thrivikraman** is currently an RF engineer at the Jet Propulsion Lab at the California Institute of Technology in the Radar Science and Engineering section where he has focused on the development of RF hardware for air- and space-borne SAR imaging systems. He received his PhD in Electrical and Computer Engineering from the Georgia Institute of Technology in 2010. His research under Dr. John Cressler in the SiGe Devices and Circuits Research Group at Georgia Tech focused on SiGe BiCMOS radar front-ends for extreme environment applications.

**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