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High Efficiency, High Linearity GaN HEMT Amplifiers for WiMAX Applications

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GaN HEMT power transistors are a key enabling technology for successful design of WiMAX radio systems. This article demonstrates the performance enhancements offered by new transistor products.

Worldwide Interoperability for Microwave Access, better known as WiMAX, is a standards-based wireless technology for providing high-speed, last-mile broadband connectivity to homes and businesses as well as for mobile wireless networks. With the fixed version of WiMAX, based on IEEE 802.16-2004, transmissions can potentially carry data traffic over more than 30 miles (~50 km) in rural areas, 6 miles (~10 km) in suburban areas, and 3 miles (~5 km) in dense urban areas. The technology is seen as both complement and successor to Wi-Fi, which sends data over shorter distances. The fixed version of WiMAX can provide data rates up to 75 megabits per second (Mbps) per four-sector base station. WiMAX will be instrumental in bringing broadband wireless to homes and offices, providing the backhaul for Wi-Fi hotspots, and eventually connecting users to the Internet in places not covered by 802.11. In those parts of the world lacking a well developed wired infrastructure, 802.16 offers a practical way to extend service to many different parts of a country, such as China or India. WiMAX can bring broadband access into the homes and businesses of millions of people in rural and developing markets.

System / Region	Frequency Band (GHz)
North America	2.4 – 2.9 5.8
Europe	3.3 – 3.9 4.9 – 5.9
S. Korea	2.3 (WiBro)
Rest of World	3.3 – 3.9

Table 1 · Worldwide WiMAX frequency allocations.

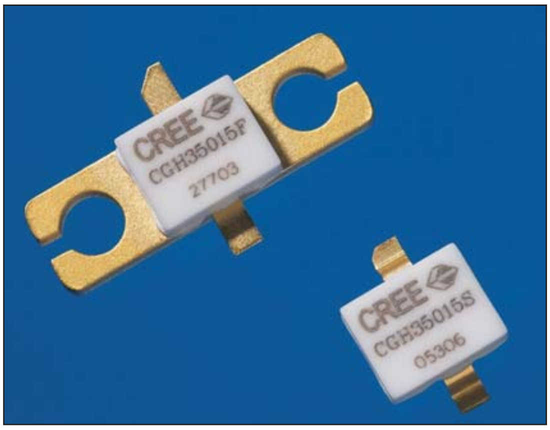

Figure 1 · CGH35015 flanged and surface-mount package alternatives.

Table 1 shows a summary of the various allocated frequencies for WiMAX worldwide including those bands that are already populated with other services. For example, WiMAX services that would use the so-called BRS (broadband radio services) band around 2.5 GHz may have to be compliant to transmitters that are co-located so there are strict FCC regulations (04-258) that require adherence. In general the average output powers required under either standard or proprietary modulation/data schemes are in the range of 1 to 4 watts for fixed access and 20 watts for mobile scenarios compliant to IEEE 802.16. In general transmitters need to adhere to both

Specification	CGH35015	CGH35120
Bandwidth (GHz)	3.3 – 3.9	3.4 – 3.8
Gain (dB)	12.0	11.0
Linear Power (W)	2.0	12.0
EVM (%)	2.0	2.5
Efficiency (%)	24	20

Table 2 · WiMAX amplifier specifications.

ACPR and mask requirements such as ETSI EN 301 021 v1.6.1. This places constraints on the linearity of the power transistors used in both the driver and output stages of the transmitter. The goal of transistor suppliers is to provide components that not only achieve adequate linearity but also the highest efficiencies and gains possible at relevant carrier frequencies.

GaN HEMT Power Transistors

Wide bandgap transistors such as gallium nitride high electron mobility transistors (GaN HEMTS) have been recently introduced commercially. These devices, which operate at voltage rails of 28 to 50 volts, offer much higher RF power densities than either GaAs MESFETs or LDMOS FETs. Apart from offering smaller size, the transistors have low capacitances per watt, very high transconductance (and hence gain) as well as the capability of being operated over wide bandwidths [1]. These attributes coupled with high efficiency and linearity

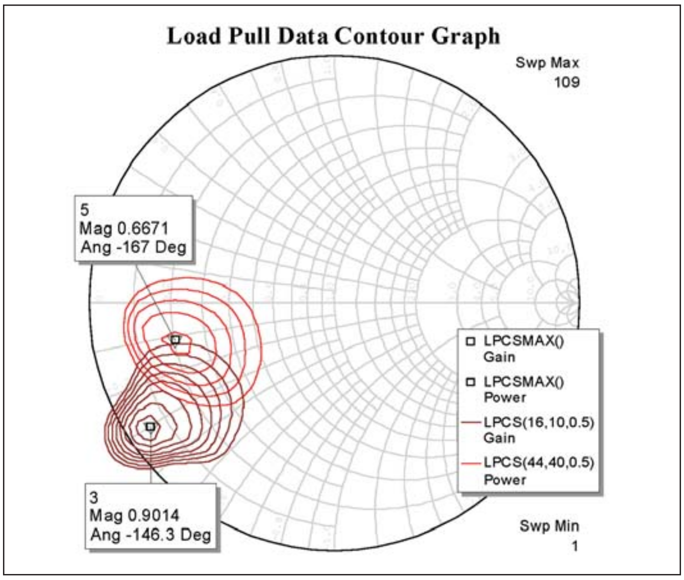

Figure 2 · Simulated source and load impedances of the CGH35015F.

under OFDM modulation make the devices ideal transistors for 2.3, 2.5, 3.5 and 5.5 GHz broadband wireless access (BWA), WiBro and WiMAX amplifiers.

Amplifier Designs using Large Signal Models

This article will cover the design of two GaN HEMT based amplifiers: a 2 watt amplifier based on the CGH35015, and a 12 watt amplifier based on the CGH35120 [2]. A summary of the specifications of these amplifiers is shown in Table 2.

Both of these amplifiers are designed to have drain efficiencies at their relevant backed-off power points of greater than 20%. Further the CGH35015 can be used as a linear driver with the CGH35120 as an output stage.

Both designs described in this article have employed Cree's proprietary large-signal models that currently support Agilent's Advanced Design System and AWR's Microwave Office simulators. These models include complete package parasitics, are broadband so that harmonic terminations can be considered in designs, allow working transistor junction temperatures to be included, and allow the simulation of two-tone intermodulation products. The latter, by comparing measured IMDs to EVM, allow a good estimate of amplifier linearity under OFDM modulation.

The CGH35015 employs an unmatched GaN HEMT die in a choice of two small "industry standard" packages. The first package (440166) is a flange-mount package and the second (440178) is a surface-mount package with gull-wing leads, both of these packages are shown in Figure 1. The HEMT is nominally operated at a rail voltage of 28 volts and a quiescent drain current, IDQ, of 100 mA in Class A/B. The simulated source and load impedances of the flange-mount packaged transistor are shown in Figure 2 at 3.8 GHz. As can be seen the output load impedance, in particular, is quite convenient for matching to 50 ohms.

A 2-Watt WiMAX Amplifier Design

The Cree GaN HEMT device has very high gain at low frequency. Stabilization circuits are included on the input of the amplifier to ensure correct operation. Distributed matching used on the input of the amplifier allows some flexibility in tuning for best performance in terms of gain, bandwidth and linearity. Figure 3(a) shows the simulated small signal gain and input return loss of the amplifier over 2.8 to 4.4 GHz. Note that the amplifier design is able to cover the full 3.3 to 3.9 GHz WiMAX band. Figure 3(b) indicates the range of tuning for S_{11} by adjusting the lengths of stubs etc. of the circuit. The

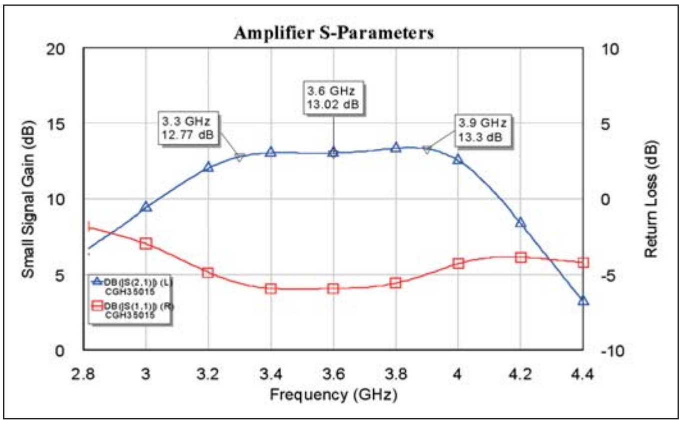

Figure 3(a) · Simulated small signal performance of the CGH35015F based 2-watt amplifier.

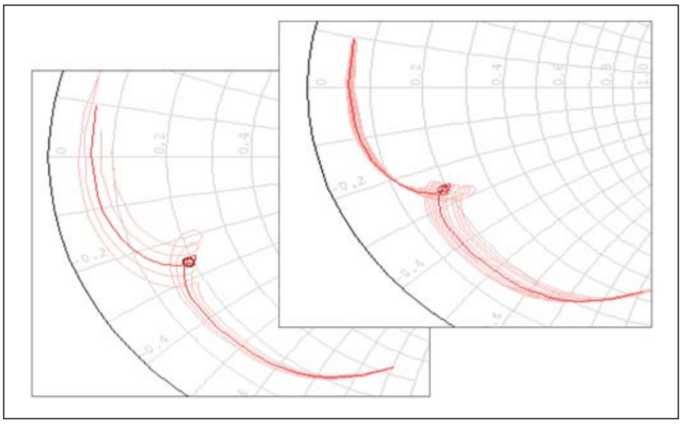

Figure 3(b) · Simulated tuning of input matching elements.

full circuit schematic is shown in Figure 4.

Moving to the output network, which again uses distributed elements; the design is concentrated on achieving acceptable IM3, IM5 and IM7 products whilst simultaneously providing the required efficiency and gain.

Note that the compression characteristics of the GaN HEMT are quite soft until P_{SAT} is reached. This is advantageous as it allows the peaks of the OFDM signal to be reproduced adequately even though the P_{1dB} gain compressed power is considerably lower than P_{SAT}. Figure 5(a) shows the simulated gain and efficiency of the complete amplifier as a function of single-tone CW output power. Note that at the backed-off power point of 2 watts the amplifier has an efficiency of 20%.

Figure 5(b) shows the simulated IM3, 5 and 7 as a function of two-tone average output power (where the tone spacing is 5 MHz). Note that there is a relatively shallow "sweet spot" around 1 to 2 watts of average power and that there is also a backed-off power "IMD hill" which has been reduced to below 30 dBc to assure that the WiMAX specifications can be met over the required 15 dB dynamic range at an acceptable level.

Figure 6(a) shows a photograph of the complete amplifier that uses Rogers 4350 printed circuit board having a dielectric constant of 3.48 and a thickness of 20 mil. Although this article has detailed the design of the flange-mount packaged transistor amplifier a very similar design exercise was carried out for the SMT packaged version. This design not only required accurate modeling of the surface mount package but also the array of vias in

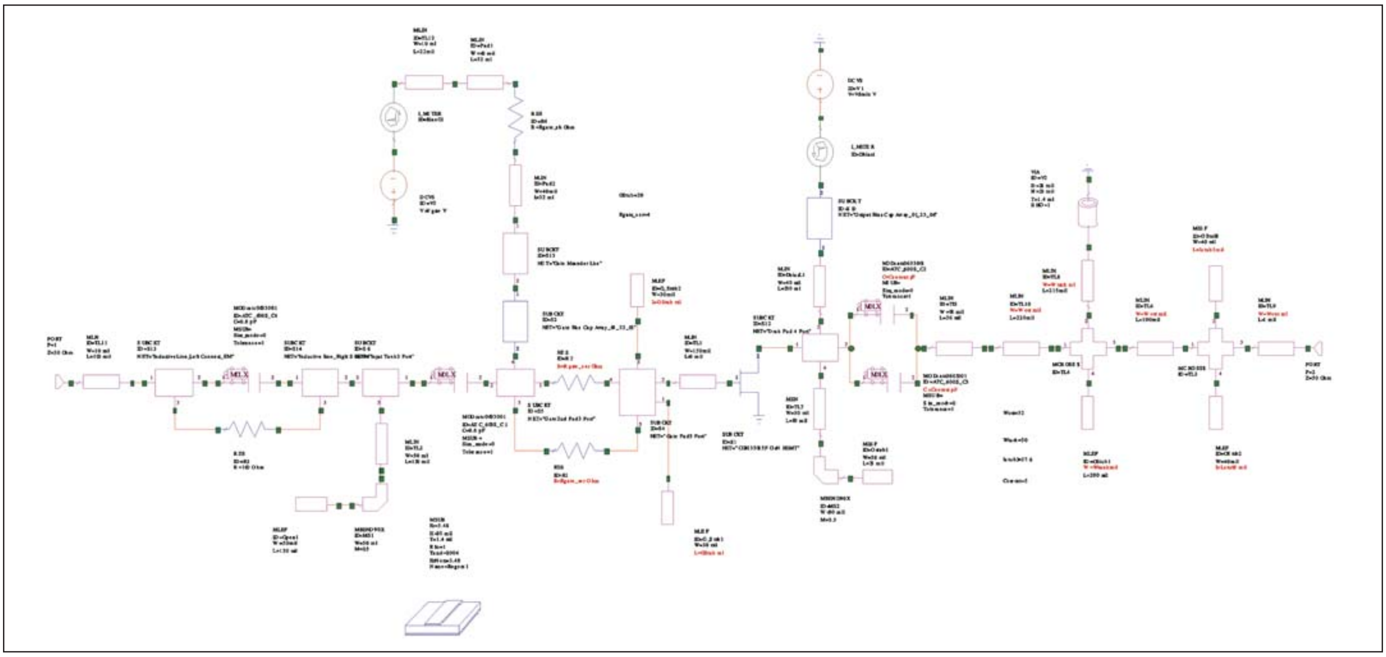

Figure 4 · CGH35015F based 2-watt amplifier circuit schematic.

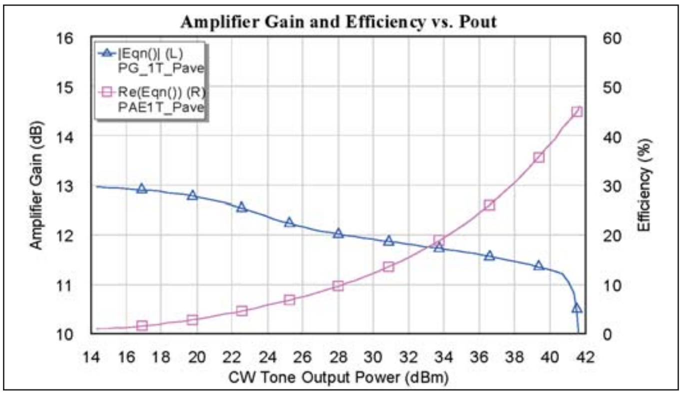

Figure 5(a) · **Simulated CW performance of the CGH35015F based 2-watt amplifier.**

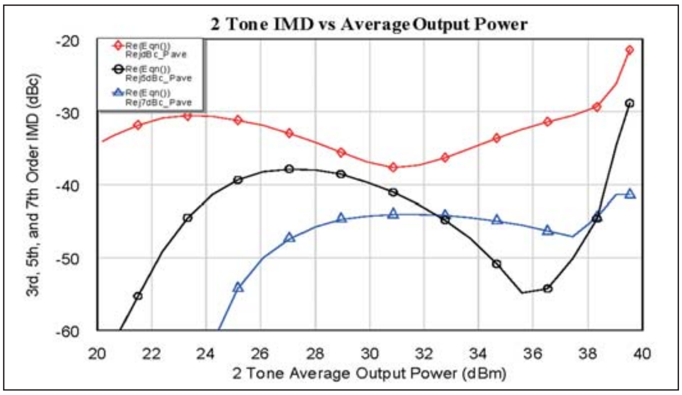

Figure 5(b) · **Simulated linearity performance of the CGH35015F based 2-watt amplifier.**

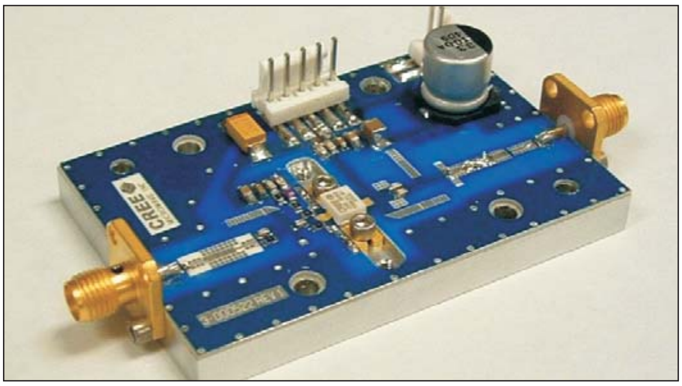

Figure 6(a) · **The CGH35015F (flange-mount device) based 2-watt amplifier test board.**

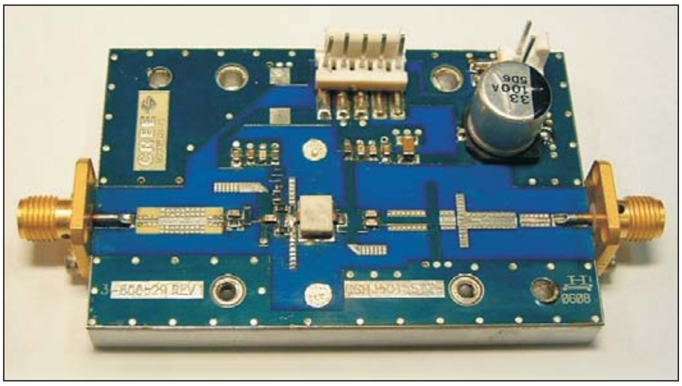

Figure 6(b) · **The CGH35015S (SMT device) based 2-watt amplifier test board.**

the PCB immediately beneath the transistor package. By these means the practical performance of the SMT version of the amplifier is almost identical to the flanged package version. Figure 6(b) shows a photograph of the SMT version of the amplifier.

Measured Results of CGH35015F

Figure 7 shows the measured small signal gain, input and output return losses of the amplifier over 3 to 4 GHz. Gain is maintained at 11.5 to 12 dB over 3.3 to 3.9 GHz. Figure 8 shows typical single tone CW gain and drain efficiency as a function of output power. Note that at 2 watts output power the drain efficiency is 18%—very close to the simulated results using the large-signal model. A typical RMS error vector magnitude (EVM) and efficiency plot taken under 802.16-2004 OFDM (3.5 MHz Channel BW, 1/4 cyclic prefix, 64 QAM modulated burst, symbol length of 59, coding type RS-CC, coding rate type 2/3) at

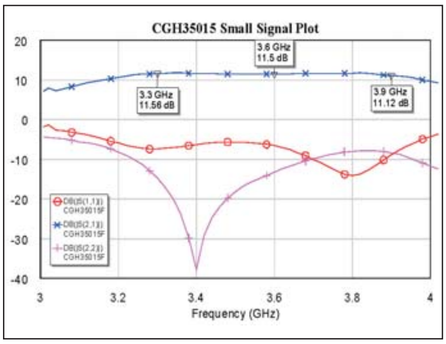

Figure 7 · **Measured small signal performance of the CGH35015F based 2-watt amplifier.**

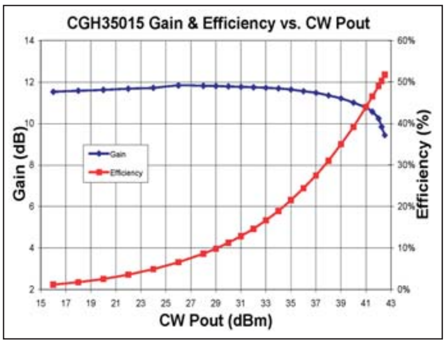

Figure 8 · **Measured CW performance of the CGH35015F based 2-watt amplifier.**

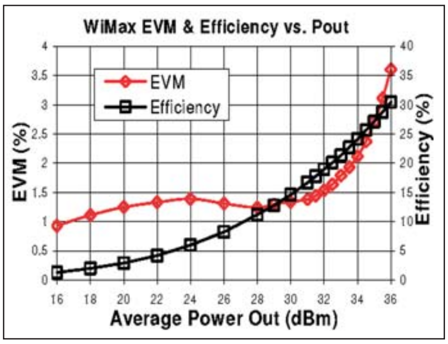

Figure 9 · **Measured linearity performance of the CGH35015F based 2-watt amplifier.**

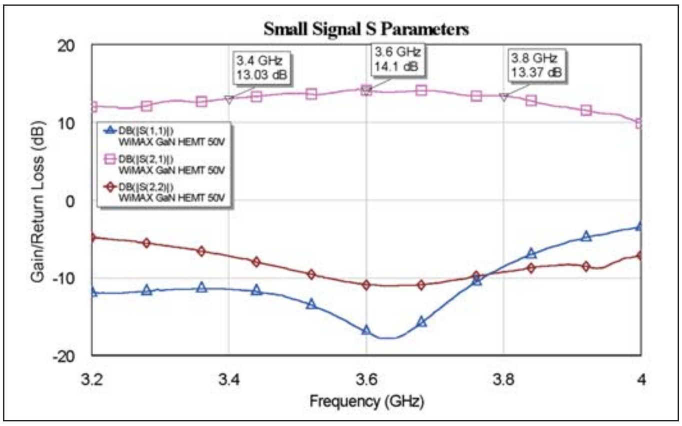

Figure 10(a) · **Measured small signal performance of the CGH35015F based 3.5-watt amplifier at V_{dd} = 50V.**

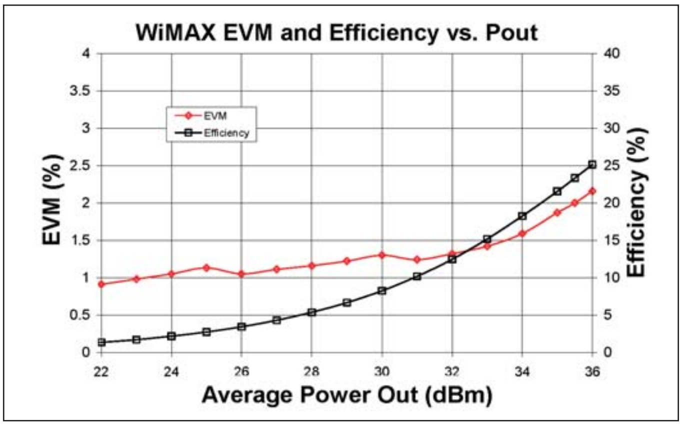

Figure 10(b) · **Measured linearity performance of the CGH35015F based 3.5-watt amplifier at V_{dd} = 50V.**

3.6 GHz is shown in Figure 9. At 2.25 watts average output power (at 2% EVM) the drain efficiency is 23%. Figure 9 shows typical EVM at average powers of 22 and 34 dBm and drain efficiency at 34 dBm as a function of frequency over 3.3 to 3.9 GHz.

The CGH35015F has also been operated at 50 volts drain bias to demonstrate the capabilities of Cree GaN HEMTs at that rail voltage. Without re-tuning the amplifier (from 28 volt operation) the results are shown in Figures 10(a) and 10(b). The gain is between 13 and 14 dB over the frequency range of 3.4 to 3.8 GHz. The corresponding average power under IEEE802.16-2004 compliant OFDM is 3.5 watts (at an EVM of 2%) at a drain efficiency of 23%.

A 12-Watt WiMAX Amplifier Design

The CGH35120 employs a single GaN HEMT die in a brazed ceramic/metal package (440193). Unlike the CGH35015 this transistor employs an internal pre-match consisting of series wire-bond inductances and a shunt capacitor attached to the flange of the package. This affords a transformation from a low real part input

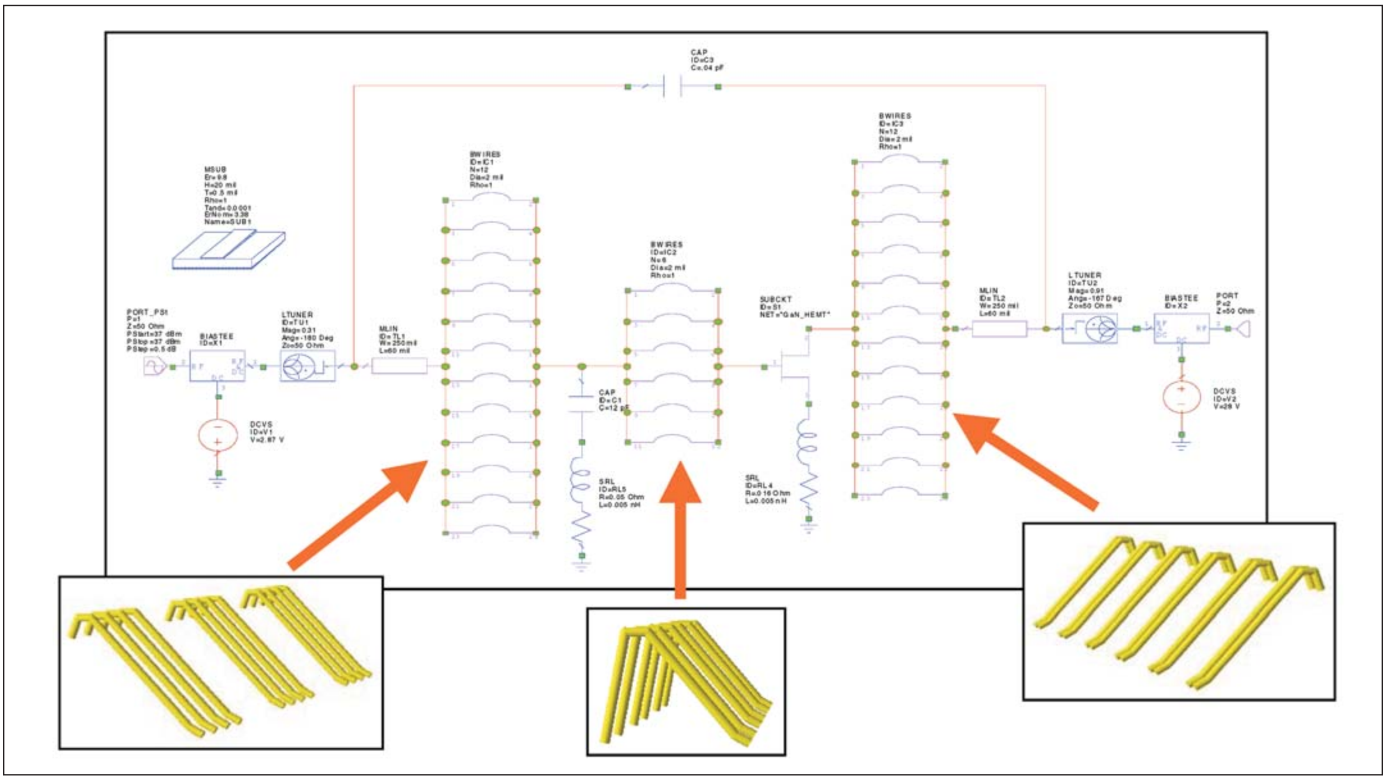

Figure 11 · **CGH35120 package model.**

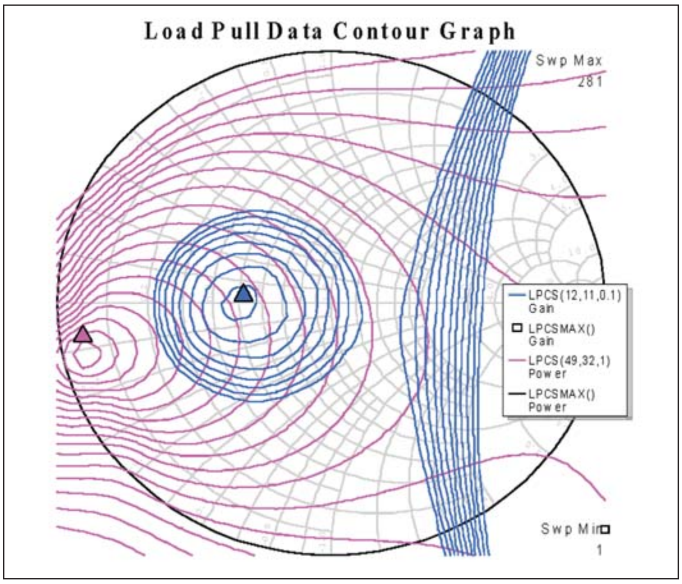

Figure 12 · Measured and modeled source and load impedances of the CGH35120. Triangles are measured impedances.

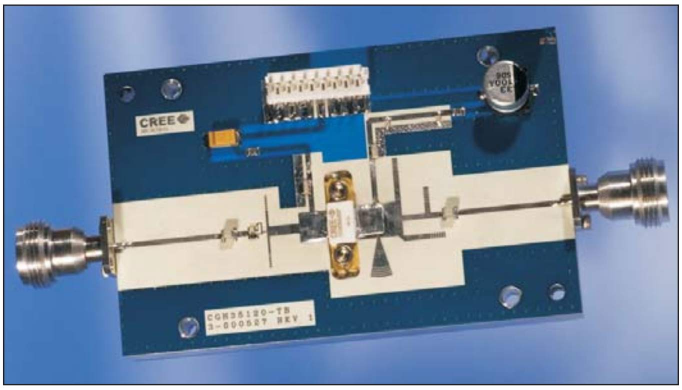

Figure 13(a) · The CGH35120F based 12-watt WiMAX amplifier.

impedance to a value much closer to 50 ohms making external input matching at the PCB level more convenient and reproducible. The internal pre-match was modeled using the Microwave Office wire-bond model (which allows definition of bond shape, length and height) for the multiple wires connecting transistor gate pads to the matching capacitor, multiple wires from the capacitor to the package flange, and the multiple wires from the transistor drain pads to the package flange (Figure 11). The package bonding areas and leads are modeled as transmission lines.

The value of the internal shunt capacitor, combined with the lengths of the wire connections from the capacitor to the transistor gate pads, is chosen to provide the transformation to a real part impedance of 25 ohms at 3.6 GHz. Figure 12 shows the source and load pull contours for the CGH35120 at 3.6 GHz provided by the model (blue is source pull) as well as showing measured values (solid triangles). The transistor is operated in Class A/B with a quiescent drain current of 800 mA and a drain voltage of 28 volts.

Figure 13(a) shows a photograph of the complete amplifier demonstrating that the PCB based transmission line matching, even for this high level of peak power, is relatively simple and convenient. No capacitors are used for RF tuning—only for DC blocking. Note the employment of a series LC, shunt resistor network on the input of the amplifier to avoid possible instabilities at frequencies around 100 MHz. Figure 13(b) shows a full schematic of the amplifier.

The amplifier was characterized over 3.3 to 3.9 GHz.

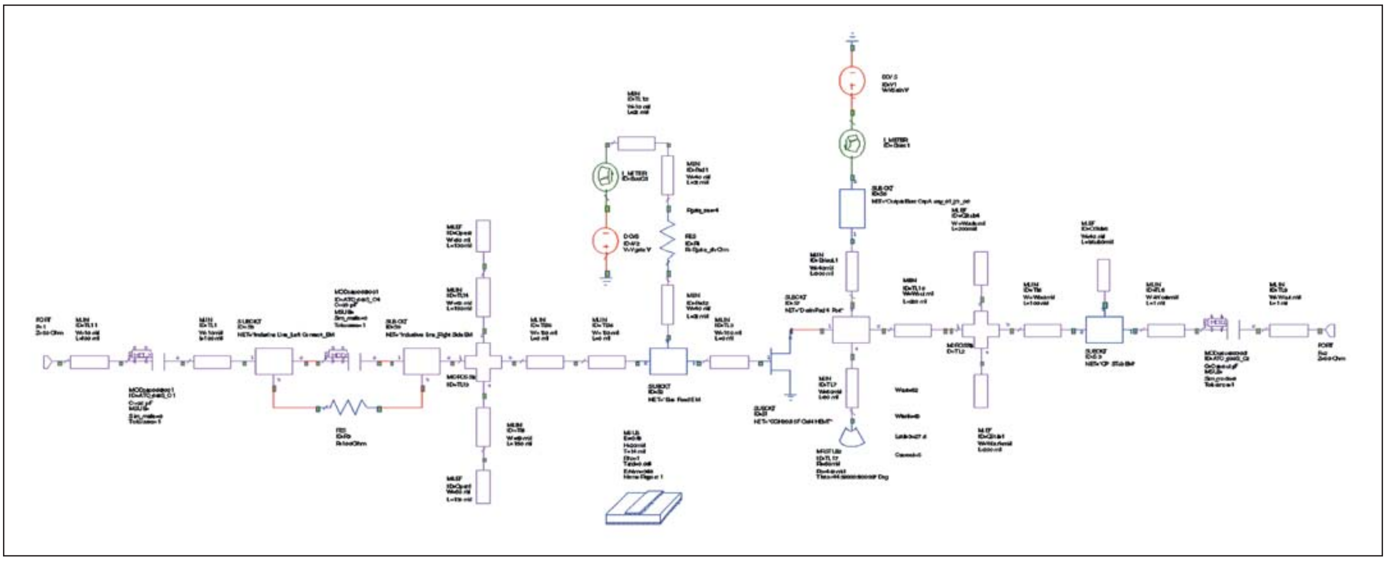

Figure 13(b) · Schematic for CGH35120F based 12-watt amplifier.

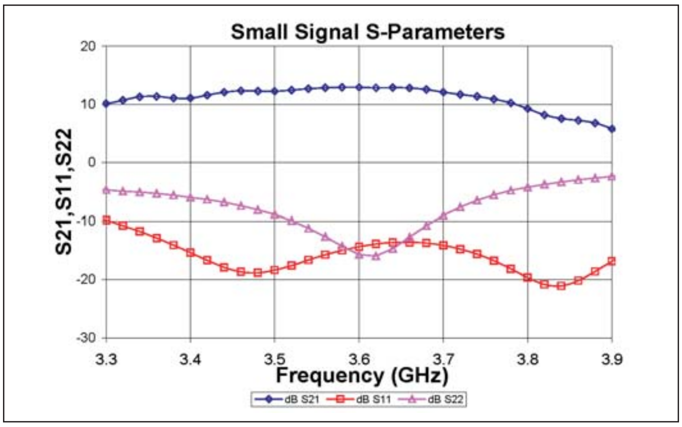

Figure 14 · Measured small signal performance of CGH35120 based 12-watt amplifier.

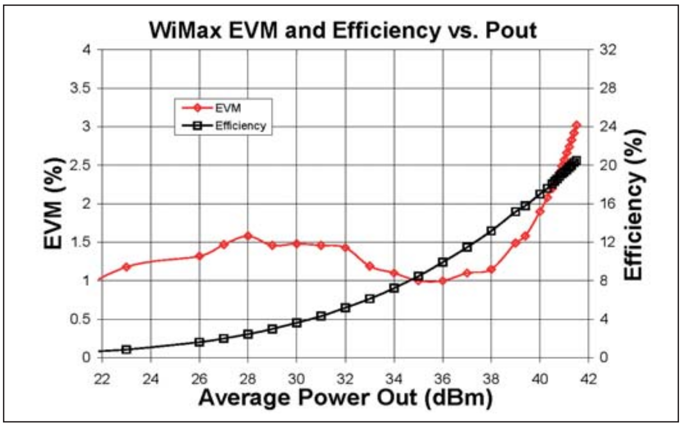

Figure 15 · Measured linearity performance of CGH35120 based 12-watt amplifier.

Small signal gain, input and output return losses are shown in Figure 14. Gain is over 10 dB from 3.3 to 3.8 GHz with an input return loss of > 10 dB over the entire band. The EVM and drain efficiency of the amplifier are shown in Figure 15 indicating that an average power of 12 watts was achieved at 3.6 GHz with a drain efficiency of 18% under IEEE802.16-2004 OFDM modulation (3.5 MHz Channel BW, ¼ cyclic prefix, 64 QAM modulated burst, symbol length of 59, coding type RS-CC, coding rate type 2/3).

Conclusions

This article has described the design and implementation of two linear WiMAX Class A/B amplifiers using Cree GaN HEMTs. Both designs, operating with peak powers of >15 and 100 watts respectively, demonstrate the broadband capabilities of wide bandgap transistors whilst simultaneously providing high linearity over greater than 16 dB dynamic range. In addition the transistors exhibit some of the highest drain efficiencies reported to date for OFDM applications. Both amplifier designs used Cree proprietary large-signal models that resulted in first pass design success.

In addition, it has been separately reported, [3], [4], that GaN HEMTs can be significantly corrected using either analog or digital pre-distortion enabling the same amplifiers to be operated at higher average powers and efficiencies.

For further information on the devices described in this article, please contact: Tom Dekker, Cree, Inc., 4600 Silicon Drive, Durham, NC; tel: 919-313-5639. Interested readers can visit the company Web site: www.cree.com

References

1. Wu, Y. et al "High-Power GaN HEMTs battle for Vacuum Tube Territory," *Compound Semiconductor*, January/February 2006.

2. Wood, S. et al "High Efficiency, High linearity GaN HEMT amplifiers for WiMAX applications," Session WSM-9 IEEE MTT-S International Microwave Symposium, San Francisco, June 2006.

3. Kikkawa, T. "Recent progress and future prospects of GaN HEMTs for base-station applications," *Compound Semiconductor Integrated Circuit Symposium*, 2004. IEEE Volume, Issue, 24-27 Oct. 2004 pp 17-20.

4. Poulton M.J. et al, "Linearity and Efficiency Performance of GaN HEMTs with Digital Pre-Distortion Correction," Session TH1B, IEEE MTT-S International Microwave Symposium, San Francisco, June 2006.

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Simon Wood graduated from the University of Bradford, England in 1995 with a degree in Electronic Engineering with European Studies and then worked for Marconi Instruments for 3 years. In 1998 he moved to the United States to work on MMIC design with Raytheon Microelectronics. Since 2000 he has been employed with Cree Inc, and has designed power amplifiers using Silicon LDMOS FETs, silicon carbide MESFETs and Gallium Nitride HEMTs. Simon is currently Manager of RF Product Development. He is a member of IEEE, a member of IEE and a chartered engineer.

R. Peter Smith has worked at Cree Inc. as a device scientist since 1999, developing GaN HEMTs for microwave power applications. From 1990-1999, he worked at JPL on III-V device technologies for applications ranging from a few GHz to 2.5 THz. He was a co-inventor of the microwave grid amplifier using differential pairs of transistors, and developed circuits combining micromachining techniques with deep-submicron air-bridged Schottky diodes for THz mixers and multipliers. He received his PhD in Physics from Brown University in 1986 and worked at GE's Electronics Laboratory on GaAs power HEMTs and MESFETs from 1986-1990.

Jim Crescenzi received the BS degree at UC Berkeley in 1961 and the MS and PhD degrees at the University of Colorado in 1962 and 1969. He worked for Watkins-Johnson Company for 27 years, followed by Spectrian Corporation for three years, then Cree Microwave for four years. He founded Central Coast Microwave Design in 2005, where he provides consulting services primarily for microwave power amplifiers and subsystems. Dr. Crescenzi was President of the MTT-Society in 1994, and chaired the International Microwave Symposium in 1996. He is an IEEE Life Fellow. He can be reached by email at jcrescenzi@charter.net, or by phone at 805-927-3563.

Bill Pribble received the BS in Electrical Engineering from Virginia Tech in 1987 and the MSEE from North Carolina State University in 1990. Employed in 1990 at ITT's GaAs Technology Center, he worked on power FET characterization and modeling, and designed power amplifiers of varying bandwidths from 1 to 18 GHz. In 1997, he moved to Cree, Inc. where he has been involved in all phases of wide-bandgap device characterization, modeling and amplifier design. He currently manages the MMIC foundry design group. He has published several papers and has contributed to a number of IEEE workshops.

Ray Pengelly gained his BSc and MSc degrees from Southampton University, England in 1969 and 1973 respectively. Ray worked for the Plessey Company from 1969 to 1986. In 1986 Tachonics Corporation employed Ray, where he was Executive Director of Design for analog and microwave GaAs MMICs. He joined Compact Software in 1989 as Vice President of Marketing and Sales. Starting in 1993, Raytheon Commercial Electronics employed Ray in a number of positions including MMIC Design and Product Development Manager and Director of Advanced Products and New Techniques. Since August 1999, Ray has been employed by Cree Inc. He is presently responsible for the business development of RF and wireless products and applications using SiC MESFET and GaN HEMT devices. Ray has written over 85 technical papers, 4 technical books, holds 9 patents, is a Fellow of the IEE and a senior member of the IEEE. He can be reached by email at ray_pengelly@cree.com, or by phone at (919) 313-5567.