

Design and Characterization of a 1-Watt Driver Amplifier for Wireless Infrastructure

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This article describes the design approach, and performance measurements for a medium-power GaAs pHEMT amplifier operating over 1.6-2.4 GHz

Variable gain amplifiers (VGA) find application in RF systems that require an amplified signal level to be instantly adjusted in reaction to a continuously changing operating

environment. Transmitters may require that the gain in the driver stage be made variable to conserve power under good propagation condition or to minimize interference to adjacent sites. In receivers, particularly for cellular base-station service, the gain of the 2nd/3rd stage LNA is made variable to prevent overloading of the subsequent stage (mixer in the superhet or DAC in direct conversion receiver) under strong signal condition [1]. In a tower mounted LNA, a relatively large output power is also needed to overcome losses in the long run of coaxial cable linking it to the radio shelter at ground-level.

Module Description

The primary components of the module are the attenuator and the power amplifier (PA) sections. The PA matching networks and input/output DC blocks are fully integrated within the module. The only external components required are the RF bypass capacitors for the supply line. The multiple-chips-on-board (MCOB) assembly results in a 26-lead surface mount component measuring $5.0 \times 8.0 \times 1.1 \text{ mm}^3$.

The voltage variable attenuator is implemented using four PIN diodes arranged in the π configuration [7]. Changes were made to the biasing network to reduce the original requirement for a 0-15V control voltage range

| Parameters | [2] | [3] | [4] | This work |
|--|---------|---------|----------|-----------|
| Frequency range (GHz) | 1.8-2.2 | 1.8-2.2 | 0.01-3.0 | 1.6-2.4 |
| Gain at min. attenuation | 14 | 23 | 16 | 11 |
| Adjustable gain range (dB) | 26.6 | 28 | 46 | 28 |
| $P_{1\text{dB}}$ (dBm) | 22 | 30 | 14 | 30 |
| OIP ₃ (dBm) at max. gain | 39.5 | 46 | 21.2 | 47 |
| PA power consumption (W) | 0.75 | 2.075 | 1.075 | 2.0 |
| LFOM [5], OIP ₃ - $P_{1\text{dB}}$ (dB) | 17.5 | 16 | 7.2 | 17 |
| LFOM [6], OIP ₃ / P_{DC} | 11.9 | 19.2 | 0.1 | 25.1 |
| Footprint (mm) | 6 × 6 | 6 × 6 | 4 × 4 | 5 × 8 |
| External components | 14 | 19 | 18 | 4 |

Table 1 · Comparison with specifications of other 2.0-2.2 GHz VGAs.

to 0-5V [8]. Thick bulk silicon PIN diodes with a high stored charge to resistance (Q/R_s) ratio are used to ensure linearity [9], especially at maximum attenuation (A_{max})—this minimizes degradation of the cascaded OIP₃. Using a 0~5V control voltage ($V_{\text{c_att}}$) range, the attenuation (A) can be varied over 25 dB.

GaAs pHEMT is chosen for the PA because of several desired traits. In a review of PA technologies, it is the only one (out of 8) that is simultaneously rated as “very good” in linearity and “high” in efficiency [10]. In our opinion, it is more reliable than bipolar or HBT for two reasons: no thermal runaway because the

DRIVER AMPLIFIER

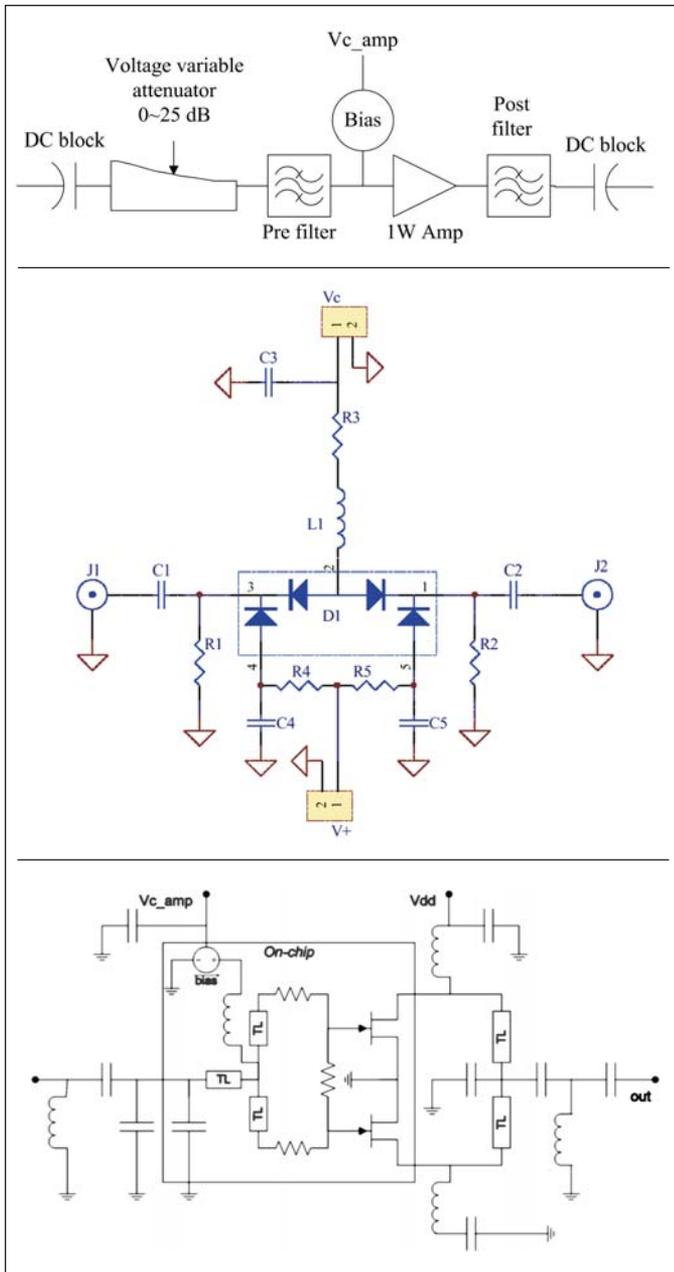


Figure 1 · (top) Block diagram of the complete VGA module; (middle) π attenuator sub-section; (bottom) Amplifier sub-section.

source to drain resistance R_{DSon} will rise with temperature, and better mismatch survivability because of the higher drain to gate breakdown voltage BV_{GD} [11,12]. The $0.25\ \mu\text{m}$ pHEMT feature size results in 60 GHz gain product bandwidth (f_T). The high f_T confers two advantages—the target gain can be achieved in just one stage and higher efficiency because the faster switching speed reduces dissipation (less time transiting the active region). Additionally, the enhancement-mode process allows direct

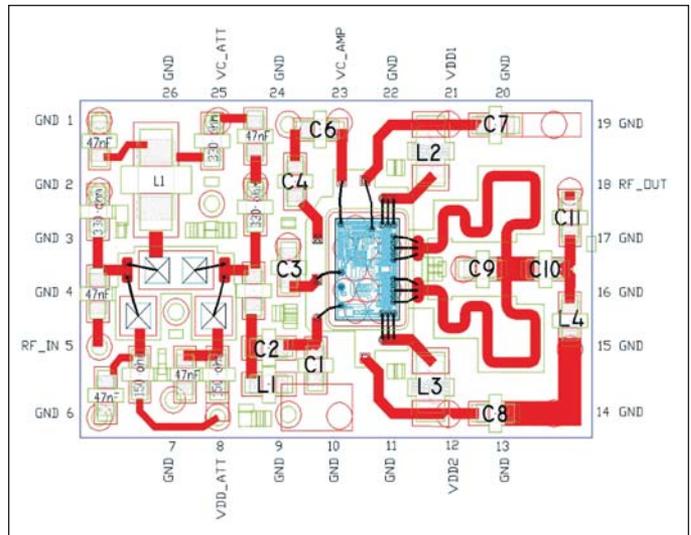


Figure 2 · Layout of the MCOB module.

grounding of the source [13]—eliminating the source capacitor/resistor combination and the accompanying parasitics which can reduce gain [14] and efficiency [15]. Two $3900\ \mu\text{m}$ FETs are combined in parallel [16] to achieve the 1W power output. Even heat distribution over the chip area is ensured by a combination of wide gate-gate spacing and the pHEMT intrinsically planar structure [17]. The input match consists of a distributed on-chip section and a off-chip capacitive tap section [18] realized with lumped components for wideband performance and reduced sensitivity to (external) component variation. Output match is also dual section comprising meander lines and lumped LC components. The operating point can be varied from class A to AB via adjustment of the control voltage (V_{c_amp}) to permit tailoring the linearity-efficiency balance to suit either the modulation Peak to Average Ratio or driver/low-power PA slot. Temperature-compensation in the internal bias is realized by using mirror FETs to create a “like material” reference—that is, the bias transistors are a scaled down version ($\sim 1/20$) of the PA FET created by the same process [19].

Measurements

The measurements were made under the following set of conditions: $V_+ = 5\ \text{V}$, $I_+ = 400\ \text{mA}$, $V_{c_att} = 3.78\ \text{V}$, $V_{+_att} = 1.5\ \text{V}$, $V_{c_att} = 0\text{--}5\ \text{V}$, frequency = 2 GHz, $P_{in} = -10\ \text{dBm}$.

With the attenuator set to minimum, the overall gain was 10.4 dB at 2 GHz. The gain could be varied over a 27 dB range; this is somewhat less than anticipated because the standalone attenuator was previously characterized at +30 dB of dynamic range (DR). Feed-forward leakage, due to coupling between components, bond-wires or PCB traces, is suspected as the cause of the constricted DR; however this is yet to be verified. Gain flatness is better

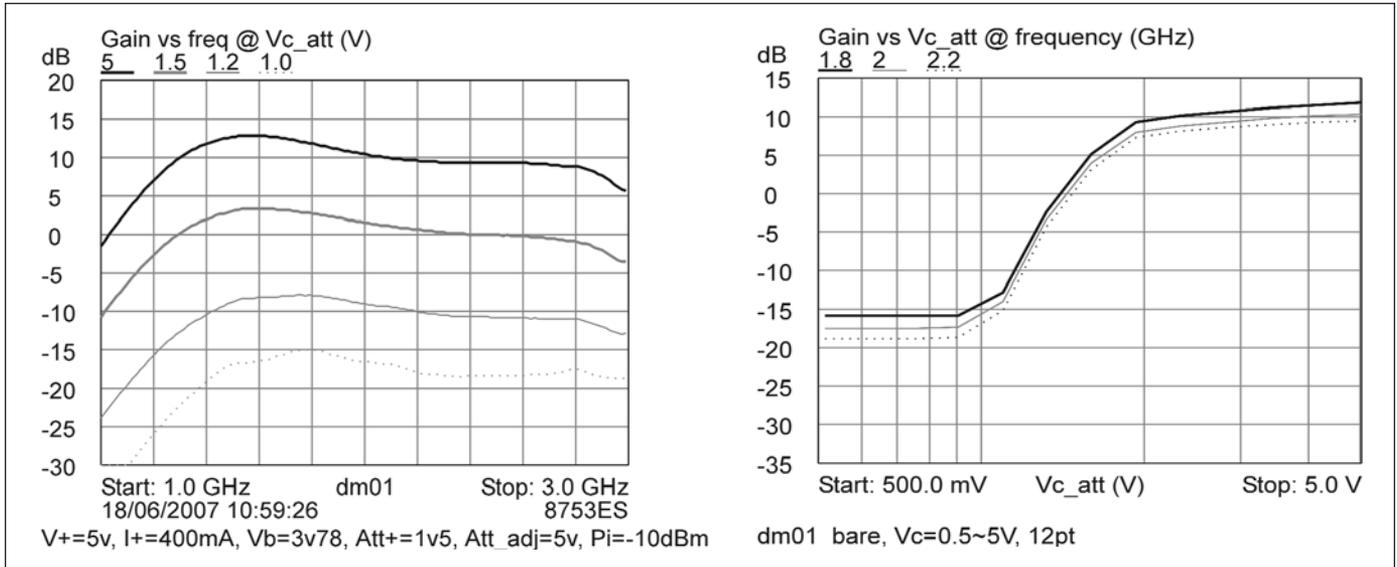


Figure 3 · (left) Gain vs. frequency as a function of Vc_att; (right) Gain vs. Vc_att as a function of frequency.

than 4 dB over an 800 MHz bandwidth centered on 2 GHz. The frequency response undergoes little change at different attenuation.

The gain at maximum attenuation is < -15 dB and increases to ~11 dB at minimum attenuation. The gain control slope is similar at 1.8, 2.0 and 2.2 GHz.

Over the target frequency range, the input return loss (IRL) remains < -8 dB, while ORL is better than -12 dB. Additionally, the constant impedance attenuator minimizes IRL variation to ~5 dB over the entire 25 dB attenuation range.

The Rollett stability factor, given by [20]

$$k = (1 + |S_{11}S_{22} - S_{12}S_{21}|^2 - |S_{11}|^2 - |S_{22}|^2) / (2 |S_{12}S_{21}|)$$

is greater than unity ($k > 1$) in the frequency range where the device has gain. The unconditional stability, for all possible source and load terminations of positive real part (e.g., $\Gamma_S < 1$ and $\Gamma_L < 1$), is attained by the use of a small resistor in series with each FET gate and by the constant-Z attenuator providing low reflection Γ_S to the FET input.

The OIP₃ was measured using two 5 dBm input tones of 1995 MHz and 2005 MHz. The best OIP₃ (~47 dBm) corresponds to the module's maximum gain setting (e.g., attenuator section adjusted to lowest loss). Generally, for attenuator loss higher than -11 dB (corresponding to Vc_att > 1.5 V), the OIP₃ was higher than 45 dBm. However, the OIP₃ drops rapidly as the attenuator's loss goes lower than -10 dB (i.e., Vc_att < 1.5 V) and finally settling down to ~30 dBm at maximum attenuation. As previously discussed, the OIP₃ degradation is primarily contributed by the attenuator section.

Other pertinent parameters include a P_{1dB} of 30 dBm

and PAE of 43% at P_{1dB}; for example, in a WiMAX PA, which is typically backed-off by 7-10 dB [21], this module is then capable of >20 dBm linear output power. The Linearity Figure of Merit (LFOM) of 17 dB, defined by

$$LFOM = OIP_3 - P_{1dB}$$

is clearly ahead of the typical value (10 dB) reported for the HEMT family [22].

Conclusion

The design and characterization of a highly integrated 1W VGA module have been described. What differentiate this module from prior efforts are a very low external part count, high linearity and efficiency. Other salient features include a compact footprint, low cost due to the MCOB construction on conventional PCB substrate, unconditional stability, and an internal bias adjust cum shutdown function which allows class A/AB variation. The integration of matching networks and DC blocks inside the module minimizes the number of external components required to less than one-third of competing designs. Future investigation will focus on locating and fixing the cause of the attenuator's reduced dynamic range.

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References

1. B. Brannon, and B. Schofield. (2006), "AN-807: Multicarrier WCDMA Feasibility (Rev 0)," [online], available at: <http://www.analog.com>.

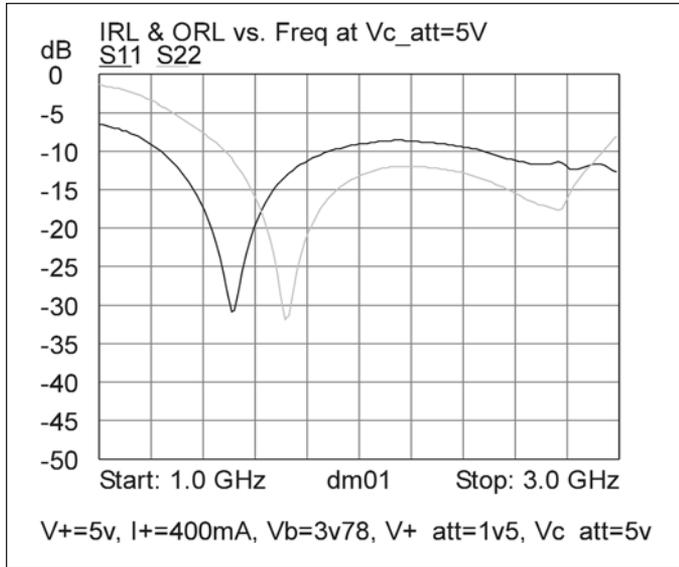


Figure 4 · Input/output return loss vs. frequency at minimum attenuation ($V_{c_att} = 5\text{ V}$).

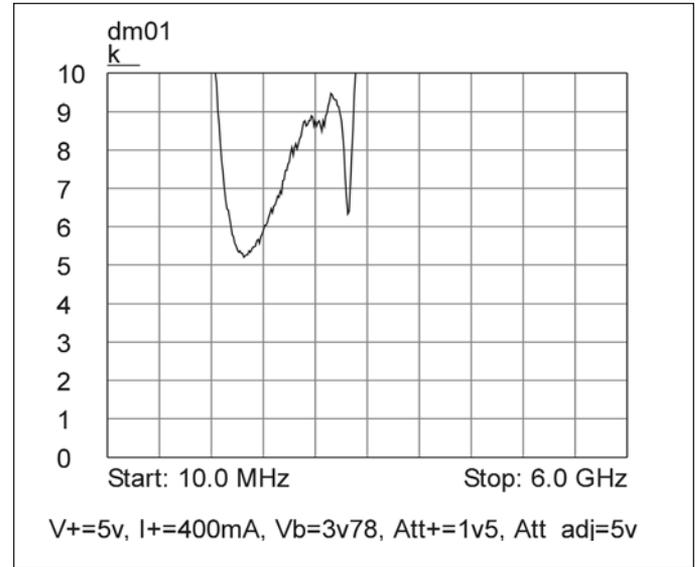


Figure 5 · Rollett Stability Factor (k) vs. frequency.

2. (2006, February), “VG111: PCS/UMTS-band Variable Gain Amplifier,” [online], available at: <http://www.wj.com>.

3. (2006, May), “VG112: PCS/UMTS-band Variable

Gain Amplifier,” [online], available at: <http://www.wj.com>.

4. (2005, June), “ADL5330: 10 MHz to 3 GHz VGA with 60 dB Gain Control Range (Rev A),” [online], available at: <http://www.analog.com>.

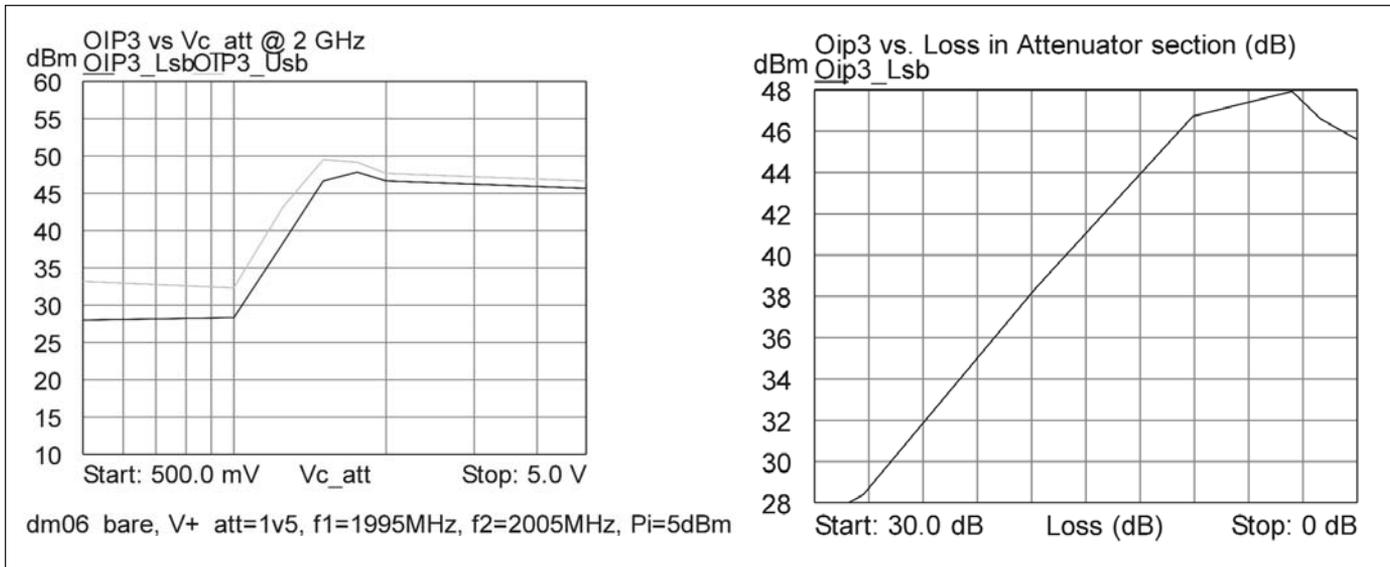


Figure 6 · (left) OIP_3 vs. attenuator control voltage and (right) OIP_3 vs. attenuator loss at 2 GHz.

5. R. S. Pengelly, "Improving the Linearity and Efficiency of RF Power Amplifiers," *High Frequency Electronics*, September 2002, pp. 26.

6. (2007, June), K. W. Kobayashi, and T. J. Hon, "400 To 3000 MHz High Dynamic Range LNAs For Wireless Infrastructure," [online], available at: <http://www.rfglobalnet.com>.

7. (1996, May), "Application Note 1048A: Low Cost Surface Mount PIN Diode π Attenuator," [online], available at: <http://www.avagotech.com>.

8. C. L. Lim, "Cut Loss In Low Voltage Wideband PIN attenuators," *Microwaves & RF*, Apr. 2008, pp. 78-86.

9. G. Hiller, and R. Caverly, "Predict PIN-diode switch distortion, Part 2," *Microwave & RF*, Jan. 1986.

10. R. S. Pengelly, "Improving the Linearity and Efficiency of RF Power Amplifiers," *High Frequency Electronics*, Sep. 2002, pp. 26.

11. (2003, April 25), "Characteristics of E-pHEMT vs HBTs for PA Applications," [online], available at: <http://www.avagotech.com>.

12. C. Weitzel, "Will GaAs Survive for Wireless PAs?," in *2005 International Conference on Compound Semiconductor Manufacturing Technology*, New Orleans.

13. (2003, April 25), "Development of E-pHEMT Technologies at Agilent" [5988-4965EN, online], available at: <http://www.avagotech.com>.

14. N. Dye, and H. Granberg, *Radio Frequency Transistors: principles and practical applications*, Newton, MA: Butterworth-Heinemann, 1993, pp. 89-92.

15. C. Baringer, and C. Hull, "Amplifiers for Wireless Communications," in *RF and Microwave Circuit Design for Wireless Communications*, ed. L. E. Larson. Boston: Artech House, 1997, pp. 384-388.

16. N. Dye, and H. Granberg, *Radio Frequency Transistors: principles and practical applications*, Newton, MA: Butterworth-Heinemann, 1993, pp. 111-113.

17. S. A. Maas, *The RF and microwave circuit design cookbook*, Norwood, MA: 1998, pp. 87-89.

18. P. Vizmuller, *RF Design Guide*, Norwood, MA: 1995, pp. 125-128.

19. C. Blair, "Biasing LDMOS FETs for Linear Operation," *Applied Microwave & Wireless*, Jan. 2000, pp. 90-94.

20. L. Besser, "Avoiding RF Oscillation," *Applied Microwave & Wireless*, Spring 1995, pp. 46.

21. P. MacIntosh, (2006, November 15), "Addressing The Ultra-Linear Requirements Of WiMAX Radio Systems," [online], available at: <http://www.rfglobalnet.com/>.

22. T. Nguyen (2005, January 18), "Choosing the Proper RF Amplifier Based on System Requirements," [online]. Available at: http://www.wj.com/documents/Articles_PDF/.

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