A 2.5 GHz WMAN Radio Demonstration Circuit

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Here is a thorough description of a 2.3 to 2.8 GHz RX/TX radio system for WMAN applications, including design parameters, measured data, and information on the devices used in the circuit

Wireless Metropolitan Area Networks (WMAN) using the IEEE 802.16/ETSI HyperMAN standard will soon be ready for deployment to deliver broadband wireless access. WMAN development is spearheaded by the WiMAX Forum of telecommunications operators and equipment suppliers, with trial deployments planned for later this year. Industry analysts expect network deployments to accelerate during 2006.

The 802.16 standard is an adaptive protocol that covers applications in the 2-11 GHz frequency range, and is meant to complement the Personal Area Network standards such as Bluetooth (802.15), and Local Area Network standards such as WiFi (802.11a/b/g). The 802.16 standard supports fixed, portable, and "nomadic" users, and is envisioned to provide a number of services, such as backhaul connection for WiFi "hotspots," broadband connectivity for industrial and educational campuses, and as an alternative to digital cable or DSL for "last mile" broadband service to businesses and residences.

The standard offers non–line-of-sight (NLOS) service, and can deliver up to 280 Mbps service to base stations using a very spectrally efficient modulation (3.8 bit/Hz). The air interface standard combines high-data-rate QAM (quadrature amplitude modulation) with multi-tone OFDM (orthogonal frequency division multiplexing), and consequently the transmitter power amplifier must be very linear to avoid distortion due to the RF carrier's peak-to-average envelope variation. This presents new challenges to the radio design engineer.

Radio Demonstration Circuit

A 2.5 GHz WMAN radio demonstration circuit was designed, fabricated and tested using Filtronic Compound Semiconductors' pHEMT process technology. A 2-stage linear power amplifier is combined with a single-stage low noise amplifier and a pHEMT-based broadband packaged SPDT switch to validate design procedures and demonstrate the basic performance specifications for a radio transmit/receive front-end. The power amplifier is designed to provide a linear 28.5 dBm output power, with less than 2.5% EVM (error vector magnitude) when an 802.16 modulation is applied. The receive path was designed to provide at least 13.5 dBm of input intercept point (IIP3) performance, referenced to a standard 2-tone measurement technique. A block diagram of the demonstration radio is shown in Figure 1.

Demonstration Radio Design

The Filtronic model FPD1000AS packaged pHEMT device was selected for the transmit (TX) path driver stage, and the FPD4000AF as the output stage, with the radio designed to provide at least +28.5 dBm linear power with less than 2.5% EVM using standard 802.11/802.16 modulations. Experience has shown that amplifiers need to be operated 7-8 dB below the maximum "linear" power level, traditionally defined as the output power at 1 dB gain compression (P_{1dB}). For amplifiers operated in Class A mode, the output 3rd-order intercept point (OIP3) is classically 10.6

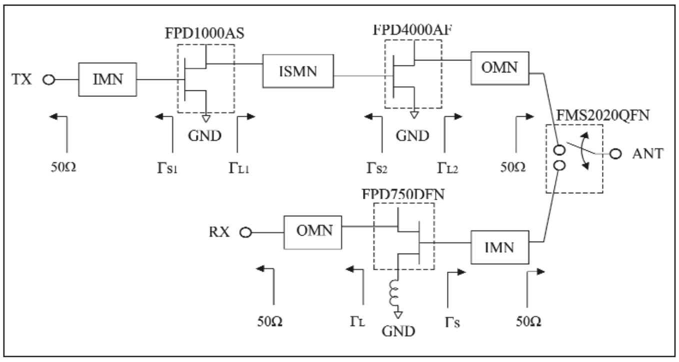

Figure 1 · Block diagram of the demonstration radio. IMN = input matching network, ISMN = interstage matching network, OMN = output matching network, and Γ_S, Γ_L = source and load impedances as seen by the devices.

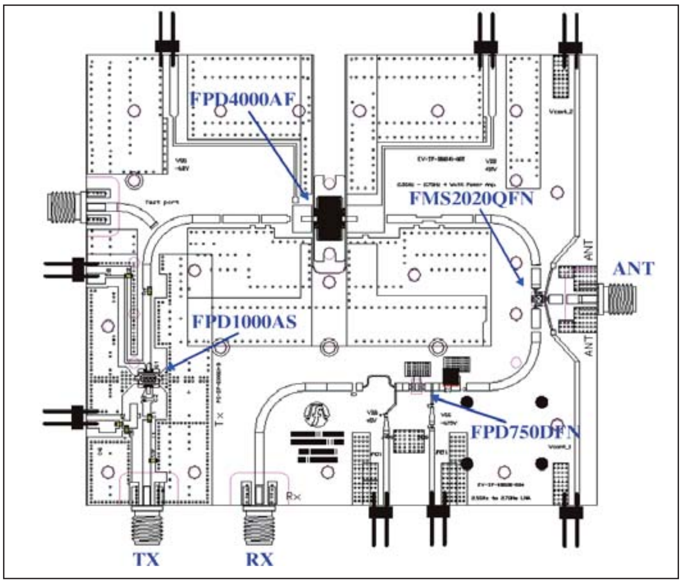

Figure 2 · Board layout, overall dimensions are 4 by 3.4 in., or 10.2 by 8.6 mm.

dB above the P_{1dB} power level, although pHEMT devices can show non-classical linearity behavior [5]. Since the intermodulation distortion performance for cascaded amplifiers follows the relationship:

$$\left(IP_T^n\right)^{-\frac{(n-1)}{2}} = \sum_{i=1}^{x}\left(IP_i^n g_{(i+1,x)}\right)^{-\frac{(n-1)}{2}}$$

where:

IP_T^n = cascaded intercept point, n^{th}-order (linear units)
n = distortion product order
IP_i^n = intercept point of the i^{th} stage (linear units)
$g_{(i+1,x)}$ = total gain following the i^{th} stage (linear units)

For a 2-stage cascade, this relationship for 3rd-order intermodulation products becomes:

$$\left(IP_T^3\right)^{-1} = \left(IP_1^3 g_2\right)^{-1} + \left(IP_2^3\right)^{-1}$$

The typical IP3 performance for the driver (FPD1000AS) is 42 dBm (15.8W), and for the output stage (FPD4000AF) it is 48 dBm (63.1W). The gain achieved by the output stage is about 10.5 dB (11.2). Thus the cascaded IP3 is approximately 46.5 dBm, a theoretical degradation of only 1.5 dB. Actual results were 46 to 50 dBm across the band. This is 12-14 dB above the P_{1dB} power level, typical non-classical behavior for pHEMT devices in a 20% fractional bandwidth design.

A convenient engineering "rule of thumb" for cascaded amplifier design is to ensure that a driver stage's output IP3 is at least 6 dB greater than the input IP3 of the driven stage. If this guideline is observed, there will be less than 1 dB of intercept point degradation of the output stage. Another caution needs to be observed in cases where the output stage does not have particularly good gain performance; the driving stage must then be selected carefully so that it does not begin to compress before the driven stage, otherwise the cascaded pair will not attain its best P_{1dB} performance.

The receive path (RX) intermodulation performance is determined principally by the low-noise amplifier stage, since the switch's output IP3 power level exceeds 38 dBm. A common difficulty with other device technologies is that the optimum DC bias current level for good noise performance is too low to simultaneously provide for a reasonable IP3 level. This is not the case with pHEMT technology, which offers extremely low noise figure performance while maintaining very good IP3 levels, thereby extending the dynamic range of the receiver. In this case, the noise figure of the FPD750DFN device is less than 0.8 dB, and the radio's input noise figure is as low as 1.2 dB, which includes the loss of the TX/RX switch. The output IP3 of the low noise stage is 25 dBm when biased at 3.3V/60 mA, and thus the input IP3 of the radio's RX path is at least 13.5 dBm. Assuming a typical receiver noise floor of –174 dBm/Hz (Nyquist noise), the receiver's operating bandwidth of 500 MHz (87 dB), and the noise figure achieved in the demonstration radio, the noise floor is –174 + 87 + 1.2 = –86 dBm. The dynamic range of the RX path is therefore nearly 100 dB.

The radio circuit board layout is shown in Figure 2. All three stages use a common source amplifier configuration and are stabilized using a shunt gate bias resistor and bypass capacitors. This stabilization technique improves the stability factor for frequencies below the passband. In

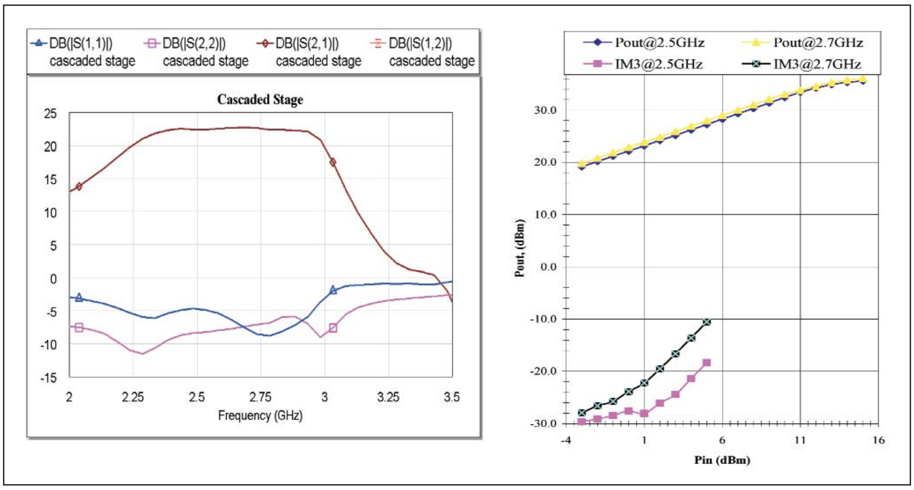

Figure 3 · Performance of the transmit (TX) path. The left-hand plot shows small-signal gain, and input/output return loss, as a function of frequency in GHz. The right-hand plot shows output power and 3rd-order intermodulation product levels as a function of input power.

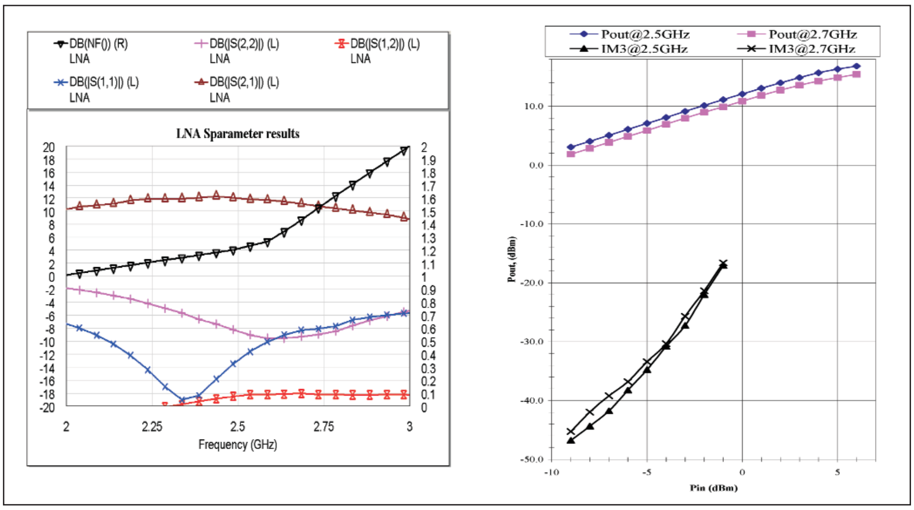

Figure 4 · Performance of the receive (RX) path. The plot at left shows the small signal gain, noise figure, and input/output return loss as a function of frequency in GHz. The other plot shows output power and 3rd-order intermodulation products as a function of input power.

the first TX path stage, the FPD1000AS pHEMT device's input is conjugately matched for maximum gain. An inter-stage matching network between the first and second TX path stages provides the optimum Γ_{L1} (output match) for the output of the first stage. The output match presented to the first stage is designed to provide an optimum power match for that stage, and the network also provides a conjugate match for the input of the second stage, the FPD4000AF pHEMT device. This interstage network is actually composed of two subnetworks to simplify the design process. The second stage output matching network transforms a standard 50-ohm impedance into the optimum load for best power and intercept point performance. Both amplifier stages are operated in Class AB mode, with a quiescent operating current about 30% of the I_{DSS} (maximum drain-source current). The TX path 2-stage amplifier can be operated from Class C (lowest current) to Class A (highest current, about 50% of I_{DSS}), depending on the specific needs of the user. Figure 3 presents the performance of the TX path.

The FPD750DFN pHEMT device was chosen for LNA design. Source degeneration is used (by adding inductance) to simultaneously match the device for lowest noise figure and maximum associated gain. The inductance is realized by distributed element, a shorted length of microstrip line. The output matching network provides for optimum gain to again achieve the lowest possible noise figure performance. While the input noise figure is degraded by the passive loss of the switch, obtaining as much gain as possible from the low noise stage will minimize the effect of additional passive losses that occur after the active stage. Figure 4 presents the performance of the RX path.

The circuit board is fabricated using 0.03 in. (0.762 mm) thick substrate, and mounted onto an aluminum heat sink, shown in Figure 2. The substrate is Rogers 4003 material, and the board includes both plated thru-vias and filled plated thru-vias for grounding. The circuit media is microstrip, but includes lumped elements as well; there is a test port between the first and second TX path stages. In the present version, each stage requires separate bias connections for both the gate and drain bias, since the depletion-mode pHEMT technology requires a negative gate-to-source voltage to establish the proper operating current level. The user must manually apply control voltages for the switch. Additional versions are currently being designed that include DC-to-DC voltage conversion (to eliminate the need for a negative voltage supply), bias sequencing (to ensure the devices are biased on/off properly), and simplified control circuitry for the switch. Although the depletion-mode pHEMT

Parameter	Results
Operating Bandwidth	2.3 - 2.8 GHz
TX Small-Signal Gain	22 ±0.5 dB
TX Power at 1dB Gain Compression	35.5 dBm
TX Output 3rd-order Intercept Point	38 ±2 dBm
RX Small-Signal Gain	11 ±1.0 dB
RX Input 3rd-Order Intercept Pont	13.5 dBm
RX Noise Figure: 2.3 - 2.5 GHz	<1.25 dB
RX Noise Figure: 2.5 - 2.8 GHz	<1.75 dB
TX-RX Isolation	25 dB
DC Power	<8.5W

Table 1 · Performance of the demonstration radio.

devices require a negative gate voltage (in this dual bias design), the combination of excellent gain, superior linearity, and very low noise performance offers the designer the opportunity to achieve superior performance. Table 1 provides a summary of the prime performance specifications and attributes of the demonstration radio circuit.

Device and Process Description

The three active devices used in this product are very similar and all use the same critical gate technology. The epitaxial layers for all three devices are grown on 6 in. (150 mm) diameter substrates and is a standard AlGaAs/InGaAs/AlGaAs pHEMT design differing in Hall sheet charge and Schottky layer thickness. All utilize dry etch stop technology to achieve highly repeatable threshold voltages. In summary, the parts are fabricated using the following process steps. Device isolation is achieved by either ion implant isolation or standard wet mesa etch. Ohmic contacts are formed with a AuGeNiAu system, alloyed near 400°C. The N+ recess is a dry, selective etch process, which helps minimize parasitic resistances. The stepper-based optical gate process is a nitride-assisted T-gate structure utilizing a dry (plasma assisted) recess etch.

The RX path device, the FPD750QFN, utilizes a 0.25 micron gate length low-noise pHEMT structure ($f_T \approx 50$ GHz), and the TX path devices use a 0.5 micron gate length power pHEMT structure ($f_T \approx 20$ GHz). All devices utilize a Ti/Pt/Au system (for gate and 1st metal layer), and an electroplated Au for the interconnection layers. Backside processing consists of highly uniform thinning (±5 µm variation across the wafer) and either plated back side with through vias (power FET), evaporated metal (low-noise FET), or no metal at all (switch). All devices are passivated with layers of PECVD silicon nitride. The switch devices are manufactured with essentially the same processing steps, and consist of meander-gate pHEMT devices that are optimized for low loss, high isolation and linearity. The switch process is further optimized for lowest manufacturing costs.

Device uniformity for these process families is quite excellent. For example, a typical cross-wafer gain variation (5th to 95th percentile range) for a three stage 8-14 GHz MMIC amplifier using the 0.25 micron process is less than 1 dB (28 dB small-signal gain). This uniformity represents a substantial improvement for pHEMT manufacturing capability, and allows design engineers to consider biasing alternatives that are significantly less expensive. For example, complex active-bias networks are normally used to ensure consistent device operating current given threshold voltage variation. The uniformity achieved in Filtronic's pHEMT family of devices virtually eliminates the need for such complex bias circuits, and simpler networks (such as dual-bias or self-biased) can be used instead, at considerable cost savings.

Summary

A 2.5 GHz WMAN demonstration radio has been designed and characterized using Filtronic's pHEMT device technology. This radio front-end circuit is intended to allow system designers the means to optimize device performance for particular requirements, and is based on straightforward circuit design methodology. Additional design variants are planned to include bias circuit upgrades, as well as higher output power transmit amplifier chains. The radio is intended to meet the demanding linearity and efficiency requirements of the 802.16 WMAN standard.

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