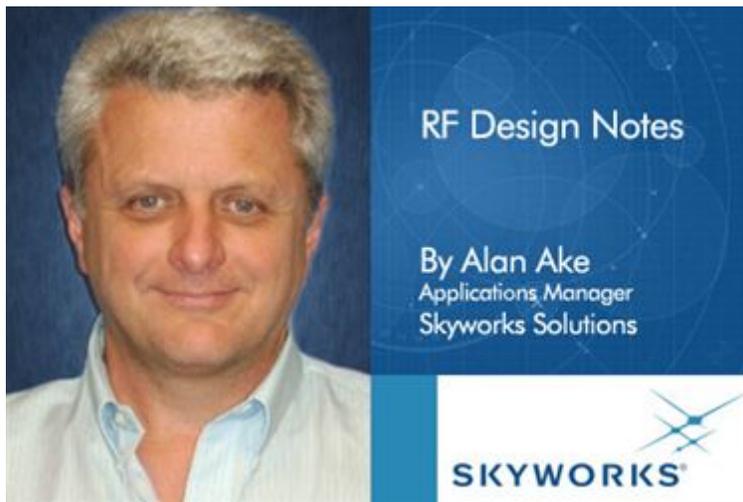




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# Rethinking The Role Of pHEMT Cascode Amplifiers In RF Design



*By Alan Ake, Skyworks Solutions, Inc.*

I consider myself fortunate that, as a fresh-out-of-school EE, I was able to start my electrical engineering career designing radio frequency (RF) front ends for what are now antiquated one-way pagers. This was back in the early 1990s, the heyday of one-way paging.

Operating at roughly 150, 450, and 930 MHz, the receiver boards for these devices employed little in the way of integration, with a discrete parts count of around 100. Initially, the only receiver integration consisted of a back-end integrated circuit (IC), which integrated the functions of second mixer and local oscillator (LO), second intermediate frequency (IF) amplification/filtering, and demodulation. What remained was a long list of matching networks and resonant tank circuits, amplifiers, mixers, frequency multipliers, and filters implemented using discrete transistors, crystals (filter and oscillator), packaged band-pass filters, and scores of discrete inductors, capacitors, and resistors.

The pager's workhorse amplifier was simply a silicon bipolar junction transistor (BJT), which had no integrated bias or electrostatic discharge (ESD) protection circuitry. Matching, biasing, stability structures, and any necessary ESD protection all had to be implemented externally using numerous discrete components. In that era, field-effect transistor (FET) devices were far too expensive, and higher performing silicon germanium (SiGe) BJTs and hetero-junction bi-polar transistors (HBTs) were either unavailable or impractical from a cost perspective. Thankfully, today's discrete designer

has many more processes and devices to choose from. High-performance indium gallium phosphide (InGaP) HBT, SiGe BJT, and gallium arsenide (GaAs) pseudomorphic high electron mobility transistors (pHEMT) are now readily available and offer ever-increasing levels of cost-effective noise figure (NF), gain, and linearity performance.

In addition to these new, high-performance semiconductor process technologies, it is now common to find discrete devices offering high levels of integration, including features such as ESD protection, pre-matching, stability enhancements, multiple amplifier stages, etc. on a single die. These monolithic microwave integrated circuit (MMIC) devices offer high performance and high levels of integration combined with small application footprints, while preserving the design flexibility that is a hallmark of discrete design.

In our role as applications engineers, we support customers working on an endless array of radio architectures and occupying frequency bands from a few hundred kHz up to 6 GHz and beyond. Successful discrete design is all about finding the optimal tradeoffs between key RF performance parameters such as gain, noise figure (NF), third-order intercept point (IP3), 1 dB compression point (P1dB), ruggedness, reliability, and efficiency, as well as application footprint and cost. As applications engineers, we have an internal role in which we routinely participate in new product definition, characterization, and qualification. This perspective, along with our constant work with such a wide variety of customers and applications, gives us some educated opinions regarding the optimal device and process for a particular application. Often, in ways that are equally important, we also know what *not* to use for particular applications.

Getting back to the old paging technology for a moment, our workhorse low-noise amplifier (LNA) architecture was the cascode for the 450 MHz UHF and 929 to 932 MHz pagers. Using silicon BJTs, which were state of the art at the time, this architecture gave us the gain, stability, and NF we needed in a cost-effective and extremely efficient way. Using bipolar transistors, the cascode is implemented as a common emitter input transistor driving a common base output stage. The key item here from an efficiency standpoint is that these two stages partition the available supply voltage between them and share the same bias current. As a point of reference, our 900 MHz cascode LNA would routinely achieve 16 to 18 dB of gain, a NF of a then-amazing 2.0 dB, all while operating from a regulated 1.0 volts Vcc and 1 mA of current. The big drawback to this low voltage and current was linearity that is abysmal by today's standards. Thankfully, the FSK modulation employed in paging was fairly insensitive to LNA non-linearity and, as is the case with many receivers, our first mixer was the limiting stage in terms of overall receiver linearity. Again, these cascode silicon amplifiers employed a pair of discrete transistors with all matching and biasing circuitry implemented discretely. In the last several years, the cascode architecture has re-emerged with high-performance MMIC devices implemented in GaAs pHEMT.

Today's pHEMT cascode MMIC devices are typically marketed as LNAs but, in the hands of a creative RF designer, they can provide superior amplifier solutions for a variety of applications. Typically biased with voltages in the range of 3 to 5 volts and with quiescent current values from 20 to 100 mA, these amplifiers offer high gain, ultra-low NF, and excellent linearity and stability with outstanding thermal and ruggedness performance. Additionally, their integrated bias circuits and ESD protection diodes keep the external parts count to a minimum.

The latest mainstream pHEMT cascodes are fabricated in 0.25 micron pHEMT, where the 0.25 micron dimension refers to the gate width of the internal pHEMT transistors. These devices replace the previous generation 0.50 micron pHEMT cascodes, with the smaller gate width devices exhibiting higher gain and NF values that are roughly 0.25 dB lower than their predecessors at a given frequency.

What follows is a brief discussion about some of the outstanding properties of these pHEMT cascode amplifiers, some potential applications that go beyond their traditional role as LNAs, and some comparisons with more traditional solutions for those applications.

### **Application: General-Purpose Amplifier**

This segment is typically the domain of Darlington gain blocks in plastic, SOT-89 packages with lower performance requirements addressed by inexpensive silicon and SiGe gain blocks, which offer the required gain along modest linearity and acceptable NF. When RF performance requirements are low and cost is the most important factor, these solutions are still hard to beat.

Often, the required performance calls for higher linearity with OIP3 values in the 35 to 40 dBm range and P1dB levels around +20 dBm. Here, a more expensive Darlington amplifier done in InGaP HBT is a common solution. Often with an integrated active bias circuit, these parts usually operate from a regulated 5.0 volt supply with fixed bias current.

Darlington designs have a few major weaknesses:

- **Thermal performance:** In order to achieve broadband 50 ohm performance, device designers usually end up with HBT transistor sizes that are smaller than what would be ideal from a thermal perspective. This means that great care must be taken so that the biasing and thermal operating conditions of the amplifier do not result in excessive transistor junction temperatures, or else long term reliability may suffer.
- **Low directivity:** This directivity is just the magnitude of the device  $S(1,2)$  in dB minus the magnitude of the gain in dB. The typical Darlington device will have a directivity of only 3 to 4 dB. As directivity becomes higher, an amplifier will behave more like a unilateral device, with better stability, better isolation from input to output, and easier matching characteristics since the input and output can be matched independently. With their poor directivity, Darlington amplifiers will only exhibit excellent input and output return losses when they are terminated with broadband 50 Ohm loads.
- **Inflexible biasing:** These SOT-89 designs do not offer a bias current control pin, which allows the device  $I_{ccq}$  to be controlled separately from the  $V_{cc}$ . Typically, the parts must be used at fixed voltages of 5.0 or 3.3 volts, and the bias current cannot be optimized for optimal efficiency.

### **Alternative Solution**

These medium- to high-performance gain block applications are an area where modern pHEMT cascode MMIC devices can really excel, especially compared to traditional high-performance Darlington devices. Previous-generation 0.5 micron LNA devices can be purchased in volume at prices comparable to those of today's best active-bias InGaP HBT gain blocks, and they offer the following advantages:

- **Exceptional RF performance:** Although requiring a small amount of external reactive matching, excellent gain, linearity and NF can be achieved over fractional bandwidths (bandwidth/center frequency) of 10 to 20%. Furthermore, these devices can typically be tuned to center frequencies from a few hundred MHz up to 3.8 GHz and beyond.
- **Flexible biasing:** The pHEMT cascode MMICs typically offer a Vbias pin, which allows the device Iddq to be set independently from the Vdd. Vdd and Iddq can be adjusted over a wide range to achieve optimal efficiency for the linearity requirements of a particular application. The same device can be used by a battery-powered application at 3.0 volts and 20 mA, or by a cellular infrastructure application at 5 volts and 80 mA. A further advantage of this Vbias pin is that the device current can be shut down simply by pulling the Vbias pin low. This pin typically draws < 1 mA, thus eliminating the need to switch the much higher current Vdd supply.
- **High directivity:** High directivity is an inherent property of the cascode architecture. Directivity values of 8 to 10 dB are common with some devices displaying directivity of more than 20 dB, resulting in high isolation performance that approaches the performance of a unilateral amplifier. Note: An example of the value of this directivity goes back to the typical LNA application in which this high LNA directivity minimizes LO feedthrough back to the antenna from the first mixer. High directivity and high reverse isolation go hand in hand.
- **Excellent thermal performance:** The pHEMT transistors of these cascode devices exhibit low thermal resistance values of around 50° C per watt. Typical bias conditions of 5 volts and 70 mA result in a maximum channel temperature that is only about 18° C above the package heat sink of the device. This thermal performance easily allows reliable, high performance operation at ambient temperatures up to 105° C.
- **High ruggedness:** Here, ruggedness refers to the ability of the amplifier to be able to survive high RF input power levels. Typical maximum RF input power levels for high-performance Darlington devices and small HBT amplifiers are roughly +15 dB. The pHEMT cascode amplifiers can typically withstand RF input powers well in excess of +24 dBm with no measurable damage or change in RF performance after several hours of exposure.

#### **Application: Driver Amplifier**

This is an area dominated both by high-performance Darlington gain blocks and smaller InGaP HBT common emitter-type amplifiers. As part of a Tx chain, a driver amplifier should display extremely low adjacent channel power (ACP) performance and low error vector magnitude (EVM) performance at its intended average output power level. As with the Darlington gain blocks, the HBT driver amplifiers are often offered only in SOT-89 packages, which result in relatively rigid bias conditions for the device. In addition to the pHEMT cascode advantages noted above, here is another attribute that makes these devices outstanding driver amplifier solutions:

- **Exceptional backed-off linearity:** With typical P1dB values in the 20 to 22 dBm range and IP3 values in the 35 to 40 dBm range, these cascode amplifiers exhibit outstanding ACP and EVM performance at power levels in the 0 to 10 dBm range. This backed-off linearity, along with the flexible biasing capability, results in a transmit lineup with optimal efficiency.

### **Application: LO Buffer Amplifier**

Often, the output power of an oscillator will need to be amplified up to a much high power level in order to properly drive a high performance mixer. This is an application in which some of the very high directivity pHEMT cascode amplifiers excel. The high reverse isolation prevents the LO from being affected by any impedance changes that might occur at the output of the buffer amplifier.

### **Conclusion**

Here is a fact that always amazed me about our old 900 MHz paging radios: When we bypassed the antenna and injected the FSK-modulated RF into the LNA, the pager sensitivity level (level at which it achieved an 80 percent call rate) was around -128 dBm on the signal generator, and that was with an LNA that boasted a 2.0 dB NF. Today's state-of-the-art 0.25 micron pHEMT LNA devices can achieve a 900 MHz NF of roughly 0.25 dB, and that would improve that -128 dBm number to close to a mind-boggling -130 dBm. We have gotten to the point where there is little, if any, meaningful improvement in NF to be had from our LNA devices. That said, these pHEMT cascode devices —especially the older generation 0.50 micron devices — can offer superior, cost-effective solutions for a range of applications that go far beyond the LNA. In particular, any designer using a high-performance Darlington amplifier should take a hard look at these older pHEMT cascode devices, since they may very well offer superior performance and efficiency at a comparable cost.

### **About the Author**

Alan Ake is an applications engineering manager for analog products at Skyworks Solutions, Inc. ([www.skyworksinc.com](http://www.skyworksinc.com)) and has 20 years of experience as an RF/microwave-semiconductor design and applications engineer. He holds a BSEE from the University of South Florida (Tampa).

### **About Skyworks, Inc.**

Skyworks Solutions, Inc. is an innovator of high performance analog semiconductors. Leveraging core technologies, Skyworks supports automotive, broadband, wireless infrastructure, energy management, GPS, industrial, medical, military, wireless networking, smartphone, and tablet applications. The company offers a large portfolio of high-performance discrete RF components, including an extensive portfolio of high performance pHEMT cascode MMIC devices to meet your most demanding requirements. Our application engineering team is available to offer product recommendations and custom tuning solutions tailored to your exact application requirements.

For more information, please visit [www.skyworksinc.com](http://www.skyworksinc.com).