Design Feature

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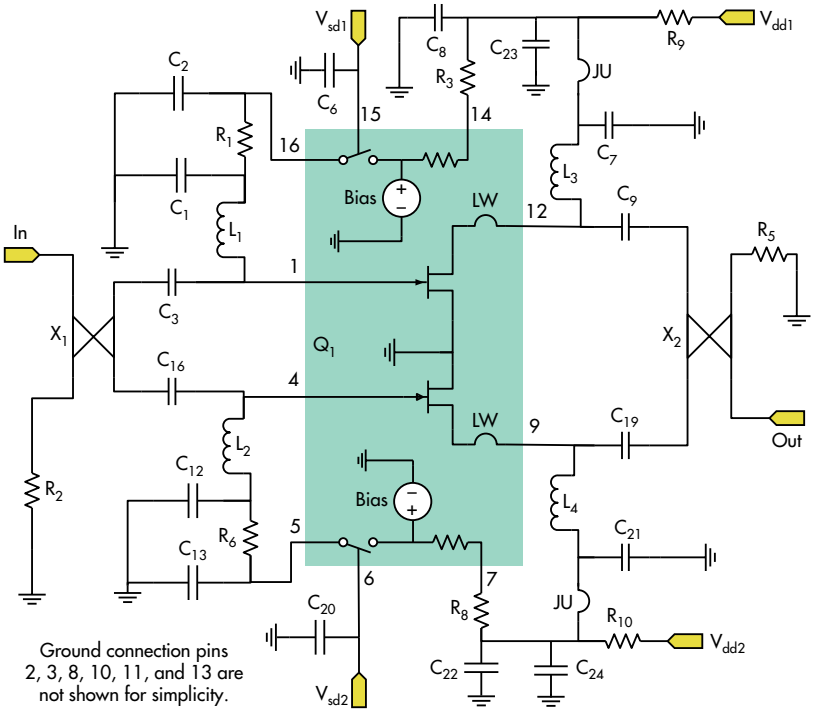
# Balanced UHF LNA Simplifies Cell Towers

**This balanced low-noise amplifier achieves low noise figure in a compact circuit while also including a shutdown mode to eliminate the need for added components in cellular communications towers.**




**1. The MMIC (yellow area) integrates dual amplifiers, active bias, and shutdown, and therefore only impedance matching and hybrid couplers are required off-chip. Components labeled JU are 0-Ω chip resistors used to bridge breaks in the PCB copper traces and are not essential to circuit operation.**

Achieving target performance goals in a cellular-communications network can be challenging because of different tradeoffs. For example, the noncoincidence of noise ($\Gamma_{opt}$) matching and conjugate $S_{11}$ * impedance matching requires a tradeoff between input matching and amplifier noise figure. Unfortunately, this tradeoff may not be available in cellular infrastructure equipment such as tower-mounted amplifiers (TMAs) because of aerial matching requirements. For example, to achieve a 14-dB aerial mismatch when a low-noise amplifier (LNA) is preceded by a bandpass filter with 18-dB return loss (assumed to be lossless), the input return loss (IRL) must be better than 23 dB. An isolator can alleviate the high reflectivity in a noise-matched amplifier, but it adds cost, size, and loss.

The balanced amplifier topology developed at Bell Labs in the 1960s[1,2] (references available in online version of this article) is an effective solution because it channels the energies reflected from a pair of amplifiers to quadrature 3-dB couplers (also known as 90-deg. or hybrid couplers) where self-cancellation can take place. Since the port match will be good regardless of the amplifiers' actual reflectivity, they can be tuned for minimum noise. Additionally, the balanced configuration has better linearity and bandwidth than its single-ended counterpart and is inherently self-stabilizing; high in-band and out-of-band stability is possible even with two potentially unstable amplifiers.[3]

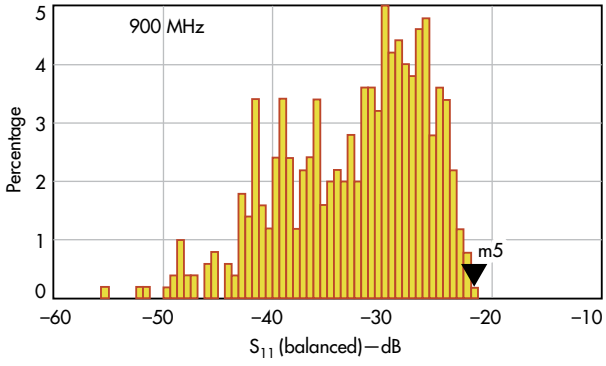
Of course, a balanced LNA has a higher parts count and power consumption than a single-ended model. Its quadrature couplers also add cost and printed-circuit-board (PCB) area, and their insertion losses degrade noise performances. If commercial drop-in couplers are used, their RF performances are generally pro-

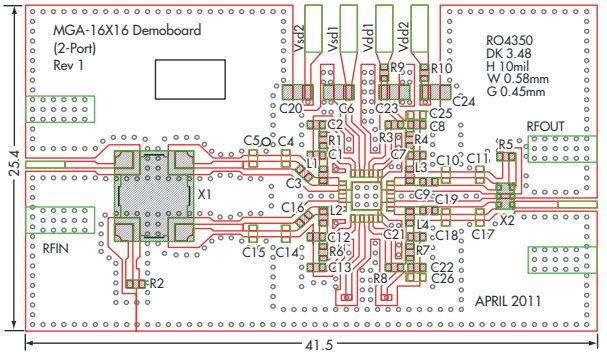
portional to their size. Furthermore, the confined space atop cellular towers does not favor balanced LNAs because they tend to be larger and heavier than their single-ended counterparts. Previous approaches to reducing balanced LNA size involved shrinking the couplers[4,5] and higher circuit integration.[6,7] However, a TMA's needs for high sensitivity and linearity tend to hamper miniaturization.

In pursuit of reduced component count and miniaturization in a balanced 900-MHz LNA, a design was developed with miniature multilayer couplers and a MMIC with integrated dual amplifiers, biasing, and shutdown functions. This may be the first time that this type of shutdown function has been integrated in a dual-amplifier MMIC. What follows will describe the materials and methods used to realize the design (see *Table 1* in online version of article). The first step in reducing the size of a balanced LNA for UHF cell towers involved the design of a new monolithic microwave integrated circuit (MMIC) that integrates dual amplifiers, electrostatic-discharge (ESD) protection, active bias circuitry, and shutdown functions (*Fig. 1*).

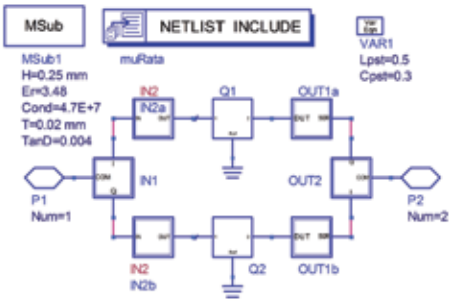
In addition to reducing the number of required external components, this MMIC combines bias circuitry and the amplifier



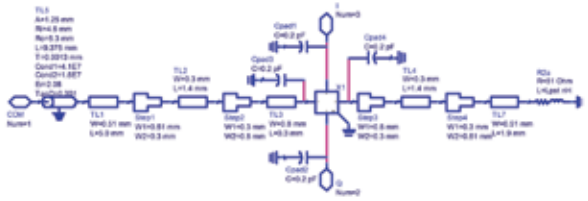

**2. Tightening the intra-MMIC $S_{11}$ difference and the coupler's isolation ensure a worst-case IRL of 21 dB.**



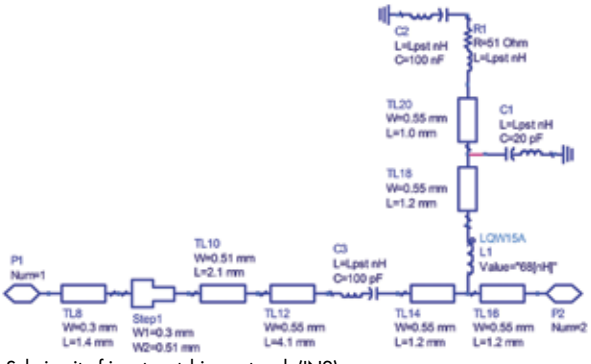

**3. These diagrams represent the PCB layout and drawing for component placement. Component positions are shown as grey-filled rectangles in a 30 × 15 mm square area (450 mm$^2$).**



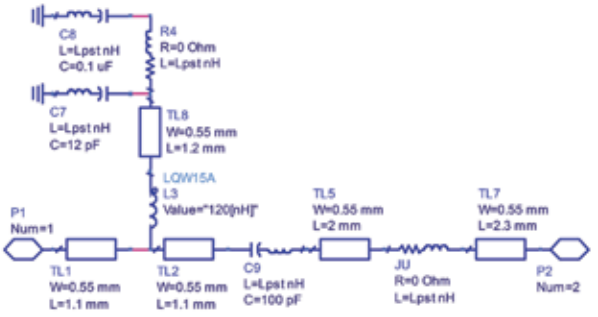

Top-level circuit model, where Q1 and Q2 are .s2p data files.



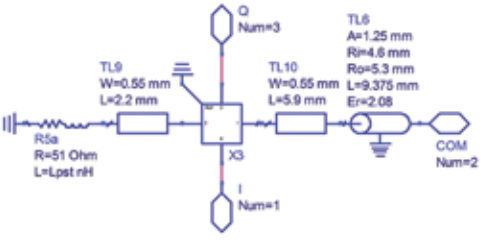
Subcircuit of input combining section (IN1).




Subcircuit of input matching network (IN2).




Output matching subcircuit (OUT1a-b).




Output combining subcircuit (OUT2).

**4. These are equivalent-circuit models for the components.**

on the same chip, with the benefit of stablizing the operating current against gate threshold voltage and temperature variations. The chip is fabricated with a 0.25-µm enhancement-mode, pseudomorphic high-electron-mobility-transistor (ePHEMT) process on a 6-in. wafer. The process offers a suitable balance of cost and performance.

The process has been proven previously through the fabrication of a single-ended LNA capable of 0.3-dB noise figure at 900 MHz,[8] making it appear that a 0.5-dB noise figure in balanced mode might be possible after factoring in the coupler's loss. The process's high transition frequency ($f_T$) of greater than 30 GHz and high peak transconductance of about 615 mS/mm make it possible to reduce the number of gain stages to just one to reach a gain level of 17.6 dB. In addition, the process is suitable for low-voltage operation because its linearity does not degrade appreciably until the drain-source voltage, $V_{DS}$, falls below 2 V.[9] The MMIC, which integrates 6 transistors, 26 diodes, 12 resistors, and 2 capacitors, is epoxy encapsulated in a 16-pin 4 x 4 x 0.85 mm quad flat no-lead (QFN) package.

The active bias circuits are connected to the voltage supplies $V_{dd1-2}$ via external resistors $R_3$ and $R_8$. Through these resistors, the gate bias voltages can be controlled by the user. Although each ePHEMT's nominal drain current, $I_{dd}$, is 60 mA at a drain voltage, $V_{dd}$, of +4.8 VDC, it can be varied from 48 to 72 mA over the usable range of values for these resistors. Inductors $L_1$ and $L_{16}$ and resistors $R_1$ and $R_6$ serve as the gates' (pins 1 and 4) bias networks. Although on-chip spiral inductors can perform this function, this design employs external inductors because they have lower losses, the smaller chip is more economical, and the chip can be used at other frequencies.

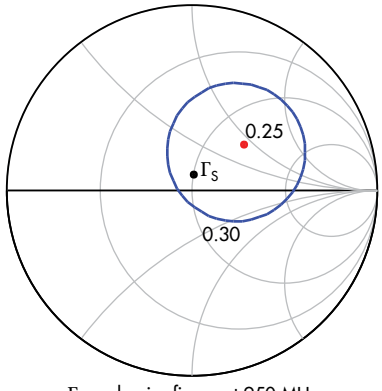
Since noise figure is critical in this application, wirewound chip inductors were used instead of multilayer inductors. Besides bias insertion, the inductors and series capacitors, $C_3$ and $C_{16}$, also form highpass networks to roll off unneeded low frequency gain. The long bondwires, $L_w$, which connect the drain to the package leads, also serve as prematching structures.

The shutdown function block consists of transistor switch in series with the active bias. Shutdown is initiated by applying a high logic (≥ 2 V) at $V_{sd1/2}$ to open the switch. Conversely, a low logic ( i.e., $V_{sd1/2} \leq 500$ mV), turns on the amplifiers. Transitioning from normal to shutdown mode takes less than 50 ns if the large (≥ 0.1 µF) decoupling capacitors $C_6$, $C_8$, $C_{20}$, $C_{22}$, $C_{23}$, and $C_{24}$ are omitted. However, these capacitors are generally recommended because they aid low-frequency stability and dampen supply transients.

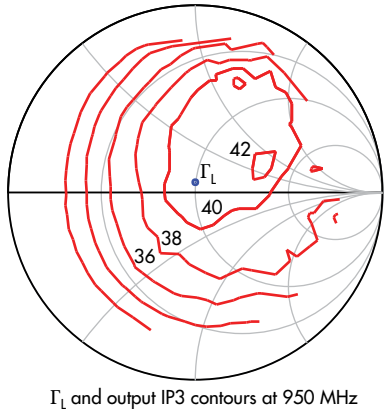
Although a Lange coupler is the most compact type of coupler component, its extremely fine trace width is not suitable for PCB implementation. As a result, the balanced LNA design uses commercially available multilayer couplers, $X_{1-2}$, to perform signal combining and splitting. A larger coupler measuring 6.4 x 5.1 mm is used at the input because of its lower loss, while a smaller

coupler measuring 2.0 x 1.3 mm is used at the output to save space and cost. To ensure that the input return-loss requirement of 21 dB or better can be met without fail in volume production, the critical parameters were identified through a Monte Carlo analysis. Subsequently, two controls were instituted: correlating the amplifiers' input match to $|S_{11a} - S_{11b}| < 0.025$ and ensuring that the input coupler's isolation is greater than 23 dB. The first control was satisfied by using adjacent chips, while the second required specifying a high-isolation input coupler.[10] The output coupler is not critical. As a result, the worst-case input return loss measured in 500 samples was 21.5 dB (*Fig. 2*).

The PCB for the balanced LNA is built on RO4350 circuit-board material (*Fig. 3*) from Rogers Corp. (www.rogerscorp.com). Wherever practical, microstrip linewidths were dimensioned for a characteristic impedance of 50 Ω. However, circuit traces next to the input coupler's mounting pads are necked down following the manufacturer's recommendations to compensate for the pads' parasitic capacitances. An FR-4 circuit-board layer was added to the 10-mil-thick PCB to increase the stack height to 1.6 mm. The input and output




$\Gamma_S$ and noise figure at 950 MHz



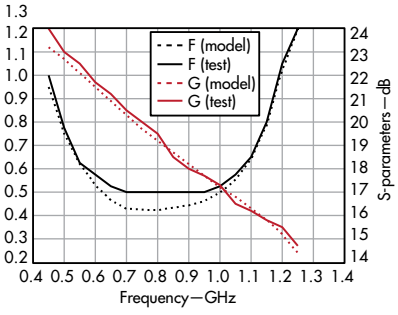

$\Gamma_L$ and output IP3 contours at 950 MHz

**5. Good noise and linearity can be obtained because the Smith chart center is encircled by the 0.3-dB constant noise-figure circle (top) and at the output side, by the +40-dBm constant IP3 circle (bottom).**

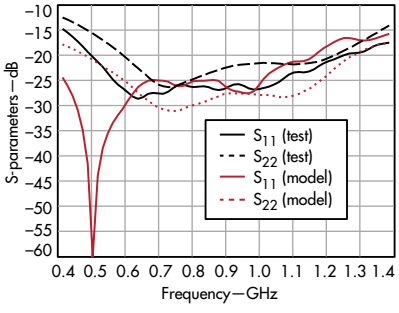
microstrip lines are transitioned to coaxial connectors using edge-launched SMA receptacles. All performance results are referenced to the coaxial ends.

Circuit simulations were performed with ADS2009 Advanced Design System (ADS) software from Agilent Technologies (www.agilent.com), with the circuit model split into a two-level hierarchy (*Fig. 4*). The upper level consists of blocks representing the MMIC, the signal dividing/combining circuitry, and the impedance-matching functions. Each dual amplifier, $Q_1$ and $Q_2$, is represented by identical two-port S-parameter (.s2p) files. The S-parameters were previously extracted on a test fixture of similar material (10-mil-thick RO4350 circuit-board material) and then applying a through-reflect-line (TRL) calibration to shift the reference planes to the package edges.

With the same test fixture, the device's noise and linearity parameters were extracted using automated source and load-pull tuners from Focus Microwaves (www.focus-microwaves.com). The ~0.2-dB $NF_{MIN}$ value is particularly challenging to extract because it can be easily obscured by the combined losses of the mechanical tuner and the required APC7-to-3.5-mm coaxial connector adapter. The inductors and hybrid couplers are modeled with their manufacturers' .s2p data. Other passive components are modeled using their equiva-




**6. The amplifier's 0.5-dB noise figure is one of the better values reported; the modeled and experimental values for noise figure and gain agree closely over a 1-GHz range.**



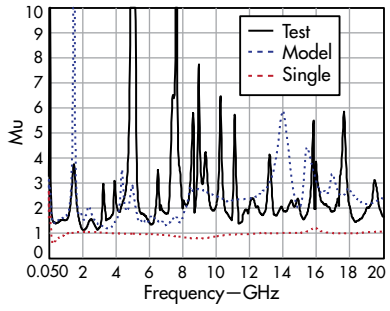

**7. These plots show modeled and measured input and output return loss versus frequency.**

lent-circuit models, including their lower-order parasitic values.

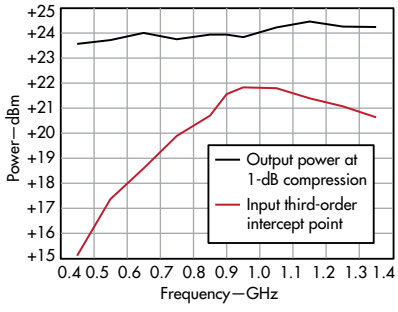
To validate the designed input and output matching networks, the modeled source impedance, $\Gamma_S$, and load impedance, $\Gamma_L$ were compared with previously measured source- and load-pull contours. The $\Gamma_S$ and $\Gamma_L$ modeled values were obtained via simulation with the ADS "S-parameter probe" component. The balanced LNA MMIC makes it easy to achieve good noise performance because the 0.3-dB constant NF circle is large and even encompasses the chart center (*Fig. 5, top*). Because of this, the input networks comprising $L_1 - C_3$ and $L_2 - C_{16}$ are designed to function as bias tees.

The absence of impedance transformations in the input LC network means that the bandwidth is not constricted by the network's loaded quality factor (Q) and the insertion loss is less sensitive to component Q. The value of $\Gamma_S$ offset from the chart center is unintentional and is due to the parasitic elements of the lumped components; the noise figure associated with $\Gamma_S$ is 0.28 dB. Any optimization of the noise match $\Gamma_{opt}$ will prove to be insignificant.

The balanced LNA circuit has an output third-order intercept point (OIP3) of better than +42 dBm at optimum output match. The area encompassed by the +42-dBm constant linearity circle will require some impedance transformation since it is located




**8. The balanced LNA is unconditionally stable (μ > 1) over a range of 50 MHz to 20 GHz despite the value of μ dipping below unity at several frequencies for the constituent amplifiers in the balanced design.**




**9. The +21.6-dBm IIP3 is the highest reported for a balanced LNA at 900 MHz.**

away from the center of the chart (*Fig. 5, bottom*). The next lower constant linearity circle, at +40 dBm, includes the chart center. Since a +40-dBm OIP3 is adequate for this application, the output network was designed without impedance transformation; i.e., $\Gamma_L = 50\ \Omega$. However, $\Gamma_L$ is shown slightly offset from the exact center because of component parasitic elements.

The LNA's PCB area is 40% smaller than the nearest competitor *(*see *Table 2* in online version of article*)*. Moreover, its single-voltage supply requires fewer components to implement than most amplifier solutions for this application. Its noise figure is as good as competing designs using larger couplers and more expensive, shorter-gate-length semiconductor processes *(Table 2*[11-15]). The amplifier's experimental noise figure and gain are 0.5 dB and 18 dB, respectively, at 900 MHz (*Fig. 6*).

The circuit model developed for this design has good predictive value because the maximum errors for noise figure and gain are 0.1 and 0.2 dB, respectively, over a 1-GHz range. If not for losses from the input coupler and matching network, the balanced LNA's noise figure would have been equal to its constituent amplifiers.[16] Since the individual amplifiers' noise figures are about 0.3 dB, it is assumed that the combined loss of the input coaxial connector and hybrid coupler is about 0.2 dB. This design can potentially serve multiple wireless communications standards (e.g., GSM and LTE) because its noise figure changes less than 0.1 dB from 600 to 1050 MHz. The noise figure increases abruptly outside this frequency range due to the input coupler's characteristics.

The experimental result surpasses the −21-dB input mismatch required by TMAs. Morever, the good impedance matching is maintained over a wide bandwidth—i.e., equal to 83% of the center frequency ($f_c$) at IRL ≤ −20 dB (*Fig. 7*). The experimental IRL is best around the input coupler's center frequency. Likewise, the output coupler determines the output-return-loss (ORL) response. The model has semiquantitive agreement with the experimental result over most of the passband. However, the experimental ORL's unexpected dip at 500 MHz was not predicted by the model, and this could be due to failure to model a component's parasitics. As previously mentioned, the quadrature couplers enable the extremely wide matched bandwidth. Both input and output return loss are limited by the couplers' finite isolation and by the microstrip discontinuities.

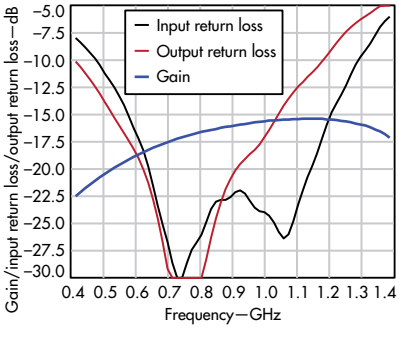
The balanced LNA is unconditionally stable even when its constituent amplifiers are not. Both modeled and measured μ stability factor exceed unity over 50 MHz to 20 GHz (*Fig. 8*). Therefore, the balanced topology's self-stabilizing promise is validated because the individual amplifiers are potentially unstable

($\mu < 1$) at several frequencies over the evaluated range.

The author notes that the input third-order intercept point, IIP3, is the highest ever reported *(Table 2)*. The output power at 1-dB gain compression (P1dB) measures about +24 dBm at midband and is relatively constant over frequency, varying less than 1 dB over a 1-GHz span (*Fig. 9*). The IIP3 was measured using –20-dBm input signals spaced 1 MHz apart, reaching +21.6 dBm at midband, or about 5 dB better than a competitive solution. But unlike the flat P1dB response, the IIP3 exhibits a pronounced peak (+21.9 dBm) at the approximate center of the couplers' passband. Referred to the output, the OIP3 is about +39.6 dBm at midband. The linearity figure of merit based on the ratio of OIP3 to DC power is about 15.7.

Activating the MMIC's shutdown function transforms the amplifier into a nonreflective attenuator which can prevent overloading of subsequent stages with about 16-dB attenuation at midband, while the input and output return losses of better than 20 dB (*Fig. 10*). Good impedance matching is maintained during shutdown because reflected energies are self-cancelled in the couplers. To the author's knowledge, this is the first time this desirable LNA property has been reported and proposed for eliminating the customary LNA bypass switch in cellular towers. The current consumption for the balanced amplifier is ~176 µA per channel during shutdown. mw

*To read the expanded version of this article, visit www.mwrf.com.*




**10. The better than 20-dB input return loss during shutdown can obviate the need for external bypass.**

ACKNOWLEDGMENTS

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