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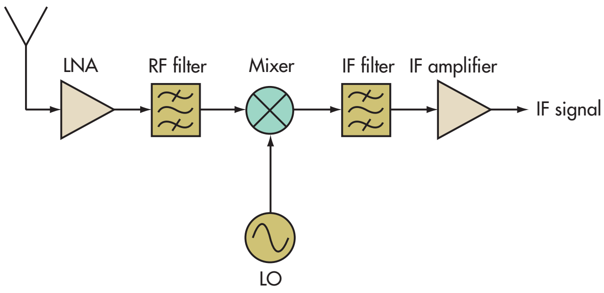
Low-Cost Front End Receives 9 GHz

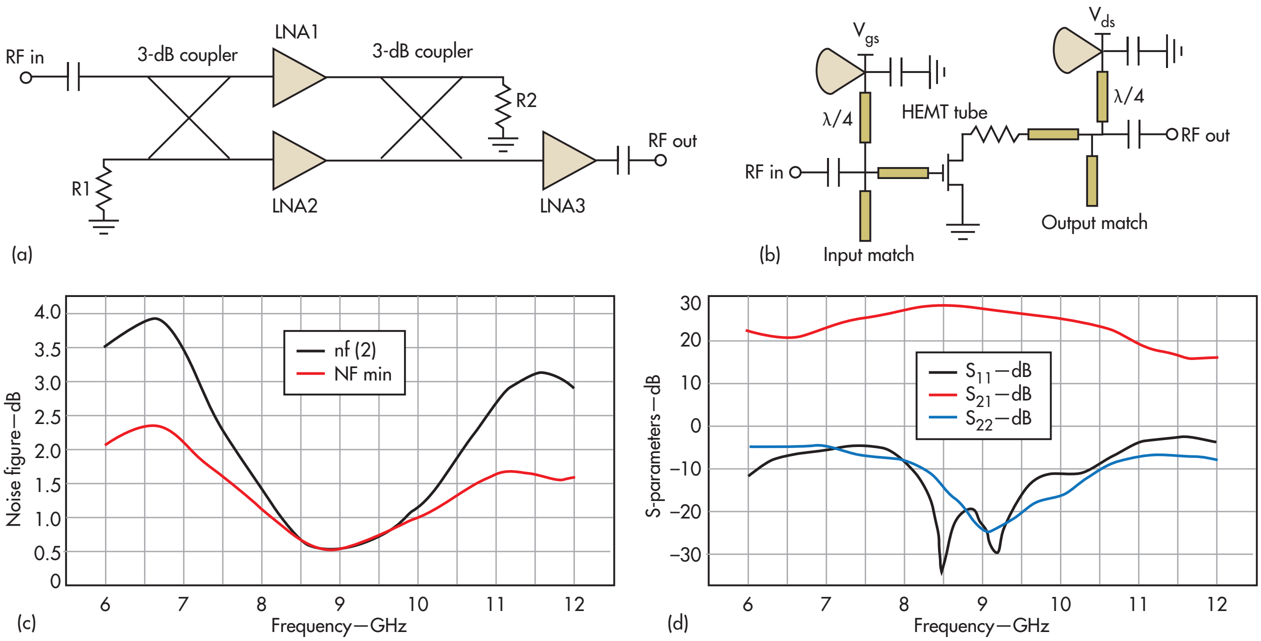
This wideband, low-cost superheterodyne receiver front end employs GaAs HEMTs with a commercial mixer, achieving outstanding performance within a 200-MHz bandwidth centered at X-band.

Increasing use of wireless systems and their services is continuing to drive data rates and consume available bandwidths. In recognition of this, the Radiocommunications Sector of the International Telecommunication Union (ITU-R; www.itu.int) has established wireless data rates to 100 Mb/s for high-mobility applications and 1 Gb/s for low-mobility applications[1] through its IMT-Advanced standards. The ITU recognizes the need to support wireless data rates to 10 Gb/s and beyond.

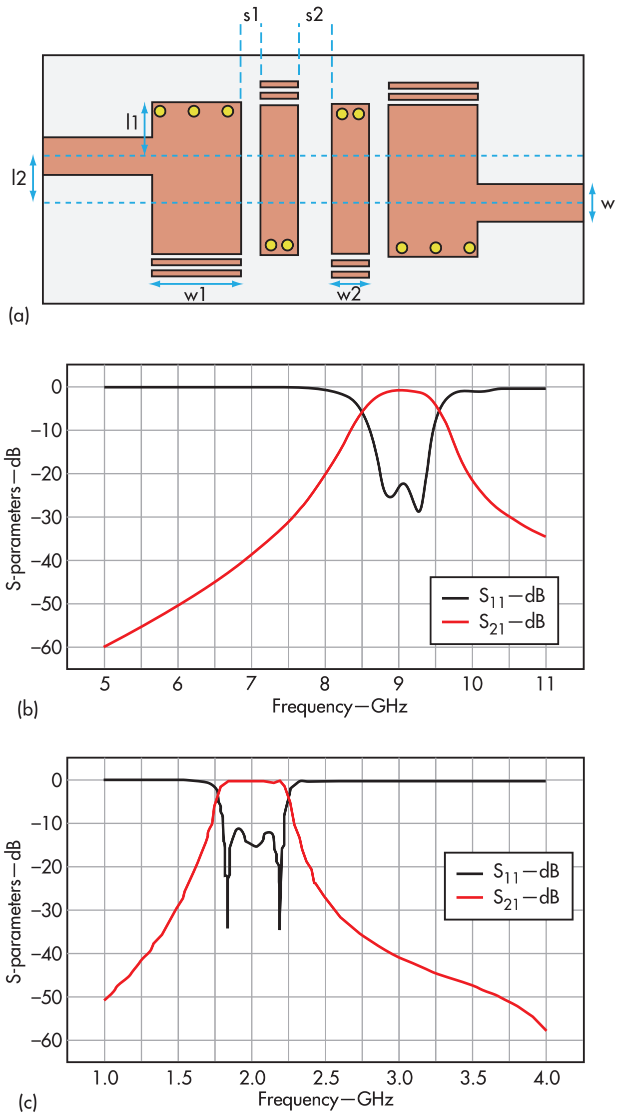
These higher data rates will require greater spectrum resources and a push to higher frequencies, such as the use of the 3.5-GHz band for the Time-Division, Long-Term-Evolution (TD-LTE) system detailed in ref. 2. Therefore, lowering



1. This block diagram shows the basic elements of the 9-GHz RF receiver front end.



2. The receiver front end includes (a) a two-stage LNA and how it compared to (b) a single amplifier, with (c) simulated noise figure performance for the two-stage LNA, and (d) simulated S-parameters for the two-stage LNA.



3. The receiver front end (a) includes RF (b) and IF filter (c) circuitry to reject unwanted signals.

TABLE 1: LINK BUDGET FOR THE RECEIVER FRONT END			
Component	Noise figure (dB)	Gain (dB)	IIP3 (dBm)
LNA	1	22	–8
RF filter	3	-3	>80
Mixer	9	-9	21
IF filter	3	-3	>80
IF amplifier	2.7	24	12
Total	2.2	32.6	>–9

the complexity and cost of a wireless transceiver's front end is vital in implementing mobile communication systems for these higher-frequency bands. As an example, ref. 3 details a receiver in the 6.1-GHz band with 100-MHz bandwidth designed to support 1-Gb/s wireless service. For systems operating beyond IMT bands, even wider channel bandwidths will be required.[4,5]

To support higher-frequency wireless applications, a wideband superheterodyne receiver was designed for X-band use at 9 GHz. The front end, which employs a commercial mixer and GaAs high-electron-mobility-transistor (HEMT) amplifiers, can be fabricated with standard printed-circuit-board (PCB) techniques and low-cost PCB laminates. It translates RF input signals to a 2-GHz intermediate-frequency (IF) band and provides a 200-MHz bandwidth at 9 GHz, with better than 3.5-dB noise figure and input return loss of better than 19 dB. The conversion gain is better than 35 dB, with gain ripple of a mere 1.24 dB. For high-speed mobile applications that require good error-vector-magnitude (EVM) performance, the front end also meets the EVM performance requirements of those systems.

As shown in *Fig. 1*, the receiver front end is composed of six parts, including a low-noise amplifier (LNA), RF and IF filters, and a local-oscillator (LO) module. A commercial mixer is used for frequency downconversion (from 9 to 2 GHz), while a two-stage gain block is used as the IF amplifier to guarantee link gain.

According to system requirements, the overall conversion gain of the receiver front end should be greater than 30 dB and the input 1-dB compression point higher than –30 dBm. With the help of the Advanced Design System (ADS) simulation software from Agilent Technologies (www.agilent.com), the different components were combined and simulated, and the link budget of the receiver front end was simulated and optimized. *Table 1* shows the final gain distribution of the RF and IF modules, as well as the simulated final noise figure, gain, and intercept points.

Compared to GaAs metal-epitaxial-semiconductor field-effect-transistor (MESFET) semiconductor technology, GaAs HEMT technology has advantages in noise, gain, and linearity.[6] In this work, a super-low-noise HEMT tube is used for the design of a low-noise amplifier (LNA). *Figure 2(a)* shows the structure of the two-stage LNA, with the two-stage (rather than single-stage) configuration chosen to provide sufficient gain. To improve input VSWR, a balanced structure is used in the first stage, with a 3-dB directional coupler employed. Since the noise figure of the two-stage LNA depends mainly on the first stage, the first-stage amplifier (LNA1 and LNA2) employs minimum noise figure matching, while the second stage (LNA3) employs maximum gain matching.

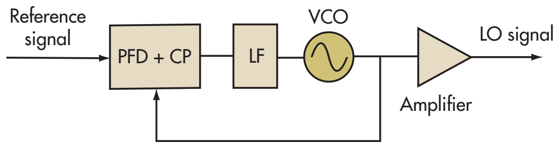
Figure 2(b) shows the circuit topology of a single amplifier (LNA1, LNA2, and LNA3). Since the HEMT tube is conditionally stable over the frequency band of interest, a small resistance is added behind it to improve stability. A band-stop filter with quarter-wavelength microstrip line and open-circuit sector stub is designed in a bias network to choke off RF transmission over its stopband, all the while maintaining optimum transmission characteristics for direct current.[7,8]

In simulations of the two-stage LNA using ADS simulation software, the LNA design yielded a simulated noise figure of less than 0.7 dB, with $|S_{21}|$ of greater than 27 dB, and $|S_{11}|$ and $|S_{22}|$ of less than −20 dB from 8.8 to 9.2 GHz.

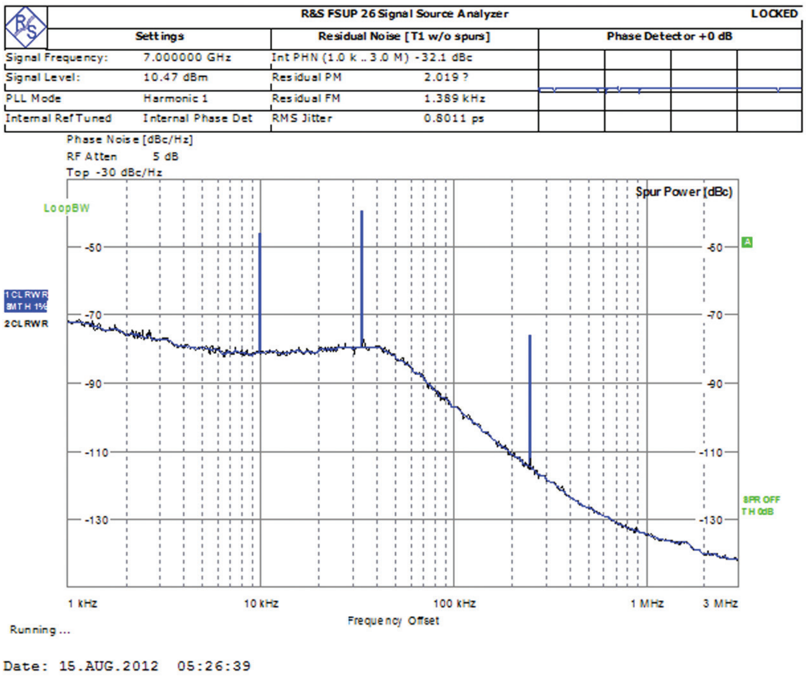
Channel filtering for the receiver front end is performed in the IF blocks by means of passive filters with high selectivity.[9] To prevent possible image-signal interference of desired signals, and to keep unwanted signals from jamming the receiver front end, an RF image-rejection filter is needed in the front end. A microstrip interdigital filter was adopted in this design due to advantages of simple structure, easy implementation, compact size, and low cost. *Figure 3(a)* shows the layout of the designed microstrip interdigital bandpass filter. Simulated responses for the filter design were obtained by means of ADS Momentum software simulation and are plotted in *Figs. 3(b)* and *(c)*.

As shown in *Fig. 3(a)*, the bandpass filter consists of an array of quasi-TEM-mode transmission-line resonators, each of which has an electrical length of 90 deg. at the midband frequency and is short-circuited at one end while open-circuited at the other end with alternative orientation. Tapped lines with a characteristic admittance equal to the source/load characteristic admittance are used for the filter's input and output ports.[8] The position of the input/output tapped line affects the filter's matching.

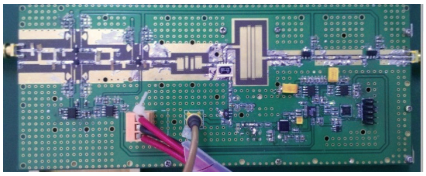
The center frequency depends on lengths l1 and l2. Coupling is achieved by the fields fringing between adjacent resonators separated by spacings s1 and s2. Coupling grows stronger with narrower spacings, and the bandwidth increases. Spacings s1 and s2 have great



4. This is the structure of the receiver front end's LO module.



5. This is the phase noise of the PLL and LO module.



6. This photograph shows the fabricated PCB of the X-band receiver front end.

influence on matching, so there are tradeoffs between the bandwidth and the reflection coefficient during the design process. As *Figs. 3(b)* and *(c)* show, the filters achieve excellent performance. The dimensions are detailed in *Table 2*.

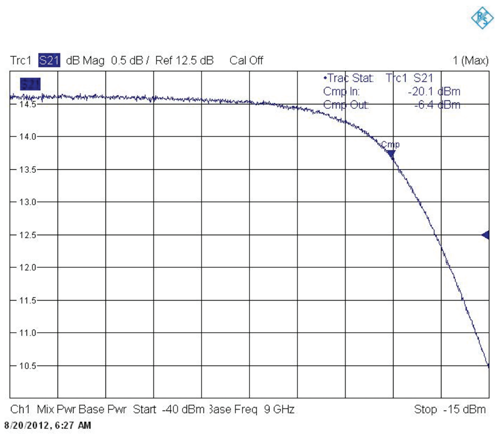
The performance of the LO module is important to the receiver front end. The LO module *(Fig. 4)* is composed of a frequency synthesizer integrated with a low-noise digital phase frequency detector (PFD) and a precision charge pump (CP), a passive third-order loop filter, and a voltage-controlled-oscillator (VCO) chip. The VCO provides the required frequency band and low-noise characteristics. A 10-MHz reference signal was provided to the LO module by a model SMF100A signal generator from Rohde & Schwarz (www.rohde-schwarz.com), which was part of the test system. The phase-locked loop (PLL) for the receiver front end is designed for an output center frequency of 7 GHz. To ensure adequate LO signal power, an amplifier was added.

To maintain reliable high-speed digital wireless communications, LO phase noise should be minimized. Within the PLL's loop bandwidth, the PLL phase detector is typically the dominant noise source; outside the loop bandwidth, the VCO noise is often the dominate noise source.[10] Therefore, the loop bandwidth is optimized to improve the phase-noise performance. *Figure 5* shows the measured phase-noise performance of the PLL used in the receiver front end. The phase noise is better than –70 dBc/Hz offset 1 kHz from the carrier, better than –80 dBc/Hz offset 10 kHz from the carrier, and better than –90 dBc/Hz offset 100 kHz from the carrier, assuming a test carrier frequency of 7 GHz.

TEST RESULTS

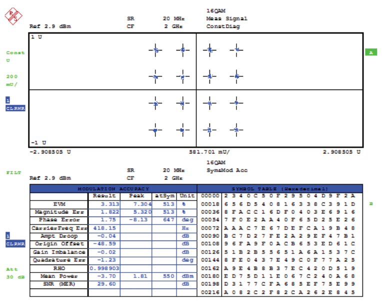
The RF receiver front end was fabricated using a standard PCB process *(Fig. 6)* and was evaluated with the aid of commercial test equipment. The measurement system included a model SMF100A signal generator, a model ZVA40 vector network analyzer (VNA), a model FSUP signal source analyzer, and a model FSQ signal analyzer, all from Rohde & Schwarz, and a model E8267D signal generator with option H44 from Agilent Technologies. Measurements were made of a variety of performance parameters, including gain, gain flatness, input VSWR, noise figure, image rejection, and input 1-dB compression point, with summaries presented in *Table 3*. The input 1-dB compression point for the entire system was measured at –20.1 dBm, as shown in *Fig. 7*. (A 20-dB attenuator was added at the IF port of the RF front end during the test to protect the input port of the model ZVA40 VNA.)

EVM is a figure of merit often used to quantify the performance of a digital radio transmitter or receiver, especially



7. These test results reveal the receiver front end's input 1-dB compression point for an input of about +20 dBm.

when it will be used for high-speed mobile wireless applications. Noise, distortion, spurious signals, and phase noise all degrade EVM; therefore, EVM provides a comprehensive measure of the quality of the radio receiver or transmitter in digital communications applications. *Figure 8* shows the EVM performance of the RF receiver front end with 16-state quadrature-amplitude-modulation (16QAM) signals. When the input power of RF signal is –30 dBm and the bandwidth is 20 MHz, the EVM levels of the RF receiver front end with 16QAM and quadrature-phase-shift-keying (QPSK) signals are 3.3% and 3.1%, respectively. When the signal source is connected directly to the test signal analyzer, the EVM is about 2%, indicating excellent RF front-



8. The EVM performance of the receiver front end was measured with a 16QAM signal.

TABLE 3: MEASURED PERFORMANCE OF THE RECEIVER FRONT END

Parameter	Measured results
Operating frequency band	8.9 to 9.1 GHz
Bandwidth	200 MHz
Noise figure	<3.5 dB
Gain	35 dB
Gain fluctuation	<1.3 dB
Image rejection	>38 dB
$\lvert S_{11} \rvert$	<–19 dB
$P_{in\text{-}1Db}$	–20.1 dBm
EVM	<3.4%

TABLE 2: RF AND IF FILTER DIMENSIONS (mm) ON SUBSTRATE WITH ε_r = 2.55 AND h = 0.5 mm

Band	w	r	w_1	w_2	l_1	l_2	s_1	s_2
RF	1.38	0.4	3.3	1.4	1.96	1.68	0.73	1.29
IF	1.38	0.4	3.4	1.5	9.68	5.68	0.30	0.49

end performance. In such applications, EVM performance is critical since stable operation is needed to preserve the relative phases and amplitudes of the in-phase (I) and quadrature (Q) signal components, such as 16QAM.

As these results reveal, the receiver front end is well suited for mobile communications within this higher-frequency band. In addition, due to its extremely low cost, the proposed front end is suitable for large-scale applications, such as in multiple-input, multiple-output (MIMO) systems. It is assembled with standard components and circuit materials and should be relatively easy to assemble. mw

ACKNOWLEDGMENTS

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