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An Integrated I-Q Mixer for Software-Defined Radio Applications

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This design case history provides a lesson in product development, describing a new microwave I-Q mixer that addresses many of the shortcomings found in earlier designs.

The software defined radio takes advantage of digital signal processing to move channel filtering, interference suppression, automatic gain control, modulation and demodulation from hardware into software. As shown in Figure 1, the block diagram for a software defined radio includes RF functions and analog and digital baseband signal processing. For simple, high volume, low performance applications, all of these functions might be implemented on a single chip. For higher performance or lower volume applications, partitioning the radio into a general purpose baseband DSP, analog circuitry using standard products, and a few RFICs is a good approach. This paper describes an I-Q frequency converter with integrated microwave splitters and phase shifters, so that the application circuit does not require any critical microwave layout techniques or off-chip components. The microwave ports are 50 ohms, the baseband ports are 200 ohm balanced, and the only off-chip component is a single non-critical bypass capacitor on the DC supply line.

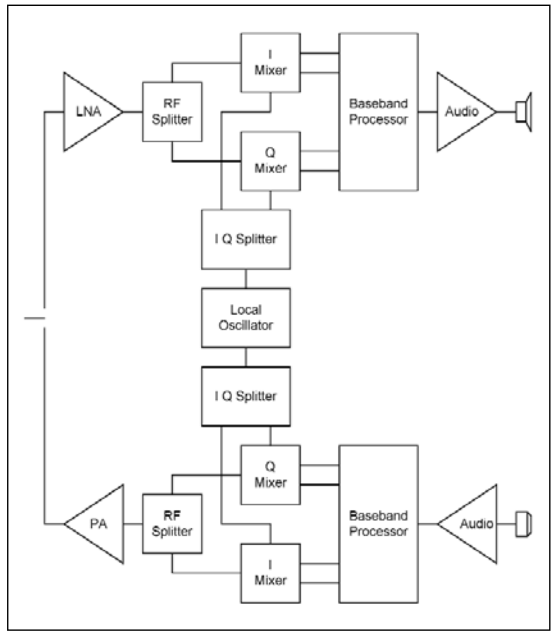

Figure 1 · Software radio architecture.

Basic Mixer Cell

A mixer for low and zero-IF applications has several important criteria in addition to noise figure, conversion loss and third-order intercept. These include 2nd order distortion, 1/*f* noise, and the suppression of LO and LO harmonics at the RF port. The conventional superhet block diagram with intermediate frequency near 10 percent of the RF input band is an old and elegant solution that avoids many problems through the judicious use of filters [1]. Optimum mixers for direct conversion receivers have been discussed in the amateur literature for several decades [2, 3] and many successful developments have been based on the pioneering work of Barrie Gilbert. The balanced mixer cell shown in Figure 2 is a recent evolution of fundamental work by Steven Maas [4] and Wes Hayward [5,6]. Similar passive MESFET mixers have been used extensively in ASICs for cellular handsets.

Two subtleties that may not be immediately apparent from the schematic are the overlaid inductor tuned LO drive circuit and the fact that the mixer FETs are operated with zero DC potential between source and drain.

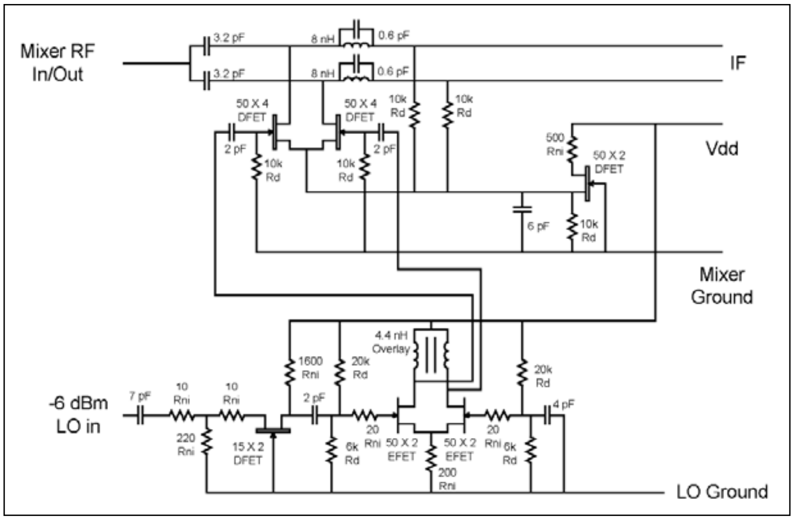

Figure 2 · Balanced mixer cell.

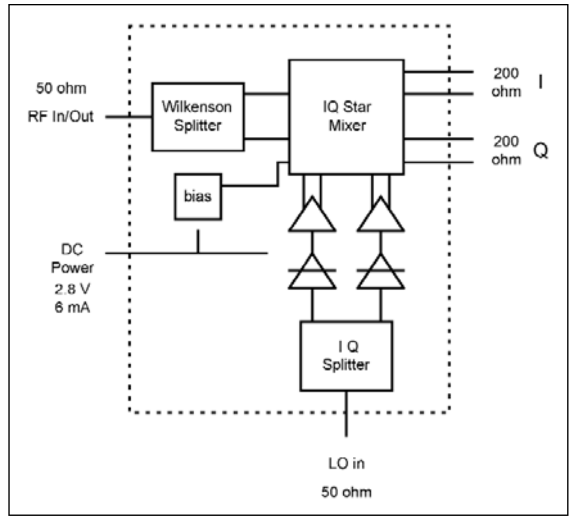

Figure 3 · I-Q mixer block diagram.

Tight electromagnetic coupling in the LO tuned circuit results in nearly perfect 180 degree balanced LO drive to the mixer FET gates. Balance is inherent in the circuit topology. Operating the mixer FETs as variable channel resistors rather than variable gain elements has a number of implications for mixer operation. First, the mixer has conversion loss rather than gain. Commercial resistive FET mixers such as the CMY-210 have conversion loss just under 6 dB, with a 50 ohm RF source and 50 ohm IF load. (Much lower conversion loss numbers, or even conversion gain, may be obtained by using step-up transformers or high impedance loads on the IF port—but such numbers have questionable merit). Not only is the conversion loss acceptably low, it is exceptionally constant. Typical production spreads of conversion loss are on the order of 0.1 dB, and pairs of IC mixers on the same die have conversion loss matched to within hundredths of a dB.

Electromagnetic coupling in the LO driver transformer and zero source-drain voltage of the FET have another interesting result: either one will cause most simulations to crash. To paraphrase Wes Hayward lecturing in a GaAs design class, "We know the mixers work—there are hundreds of millions of them in cell phones—it's the simulations that are experimental!"

One further refinement is needed for a mixer to be useful for direct conversion receiver applications. GaAs MESFET mixers are typically unsuitable for IFs below about 10 MHz due to high $1/f$ noise. The $1/f$ noise problem was attacked in three different ways. First, $1/f$ noise in GaAs MESFETs is strongly correlated with DC current in the channel. This source of $1/f$ noise is reduced by operating the device with zero source-drain voltage. Second, the density of semiconductor defects that result in $1/f$ noise is higher near the semiconductor surface. We operate the FET as a deep-channel device by biasing the gate near pinch-off. With zero drain-source voltage and a deep-channel FET, the remaining dominant source of $1/f$ noise is the pinch-off bias generator, the 100 micron DFET on the right in Figure 2. Since the bias noise is present on both mixer FETs, it can be cancelled by using a balanced IF connection. Both transformers and active balanced circuitry have been used. These three $1/f$ noise reduction techniques result a mixer with a noise figure within 1 dB of the conversion loss at 10 MHz IF and only 6 dB higher at 1 kHz IF. This compares well with other low $1/f$ noise microwave mixers.

The IF ports are DC coupled and may be shorted to ground or V_{dd} without harming the mixer cell. In normal operation, the IF ports float at V_p, the pinch-off voltage of the active devices. This is typically between 0.4 and 0.8 volts in the TQTRx process.

One final comment on the basic balanced mixer cell. This is a "one deep" circuit topology, meaning there are no series connections of active devices between DC ground and V_{dd}. Thus the mixer will operate properly as long as the supply voltage is high enough to activate the pinch-off voltage generator. This design was optimized for 2.8 volt supplies, but functions properly with V_{dd} between 1.2 volts and 6 volts. Below 2 volts, the drive to the mixer FET gates is lower than optimum, and intercept performance suffers.

The I-Q Mixer Topology

The next step is to extend the balanced mixer to an image reject design. This is where the advantage of the low loss GaAs substrate becomes evident. Signal splitters and phase shift networks may be built using standard topologies from a large catalog of active or passive circuits. Passive circuits have the

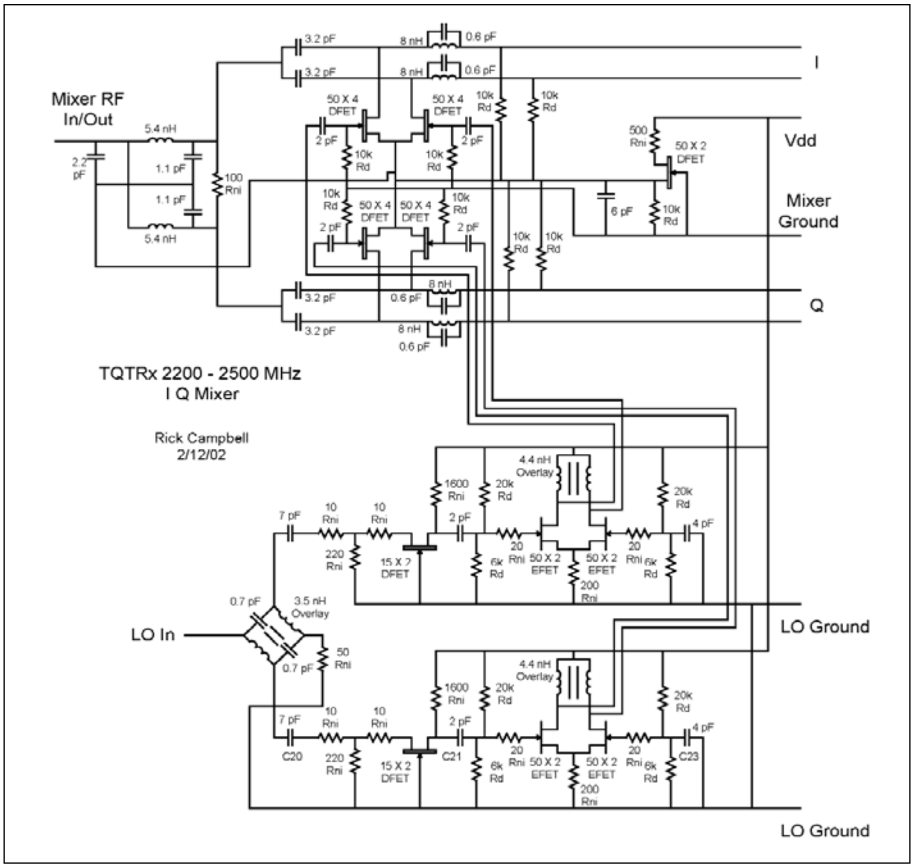

Figure 4 · Complete mixer shematic.

advantage of zero voltage and zero power operation, low noise, and low distortion. TriQuint's TQTRx process combines 0.6 micron gate E and D MESFETs with high-performance passive components including inductors and tuned transformers with Qs typically in the 30s at 2 GHz and nearly ideal MIM capacitors and nichrome resistors. Building standard lumped-element microwave passive circuits such as splitters and couplers with the mechanical tolerances available in an IC process results in amplitude and phase match an order of magnitude better than can be obtained with discrete components on a printed circuit board. As an example, a TriQuint prototype in-phase 3 dB wideband passive splitter at 2 GHz exhibits port-to-port amplitude differences less than 0.04 dB and phase differences less than 0.1 degree.

Figure 3 is a generic I-Q mixer block diagram. With well matched monolithic mixer cells, I-Q accuracy depends on the accuracy of the in-phase and quadrature splitters. Figure 4 is the complete schematic of the mixer. In the I-Q mixer, a pair of balanced mixers is split into four individual devices with a common source connection. Gates are driven by a pair of tuned, coupled transformers, assuring precisely balanced LO drive to the I/not-I and Q/not-Q mixer devices. The quadrature hybrid LO splitter has 90 degree phase shift across a wide bandwidth, but equal amplitude at just one frequency. The quadrature hybrid drives a pair of amplitude limiting grounded gate amplifiers, and the differential LO drive amplifiers are driven into compression. This results in mixer gate drive levels that remain relatively constant as the LO input drivel level varies, and also removes the amplitude variation with frequency at the output of the LO hybrid splitter. The LO quadrature splitter and amplifier system has a useful bandwidth of approximately 20 percent of the design center frequency. For example, the design centered in the 900 MHz ISM band has good performance from 820 to 1000 MHz. A direct consequence of the passive hybrid topology driving a matched pair of grounded gate amplifiers is that the input match at the LO port is unusually well matched to 50 ohms. Measured return loss is more than 20 dB from 1/2 to more than twice the design center frequency.

The RF ports are driven through a passive low-pass Wilkinson 3 dB in-phase splitter. Besides providing a good in-band match to 50 ohms, the splitter serves two other important functions. Direct conversion receivers have strong responses near odd harmonics of the LO frequency. These responses may be either external signals or harmonics of the LO itself. LO harmonics are generated by several different mechanisms in the mixer devices, including varactor multiplication by the non-linear gate capacitance. These LO harmonics can leak through the device capacitance to the RF port and reflect from unmatched impedances. Many microwave components, in particular filters, are good reflectors at harmonics of the desired frequency band. These reflected LO harmonics re-enter the mixer and result in DC offsets which degrade balance and 2nd order distortion performance. Receiver experimenters often discover that mixer 2nd order performance is a strong function of the length of 50 ohm transmission line between a narrow filter and the mixer RF port, even though the filter and the mixer are both well matched to 50 ohms in band. A low-pass filter right at the mixer RF port prevents the LO harmonics from reaching the outside world. A second function of the Wilkinson splitter is to isolate the RF ports of the I and Q mixer pairs.

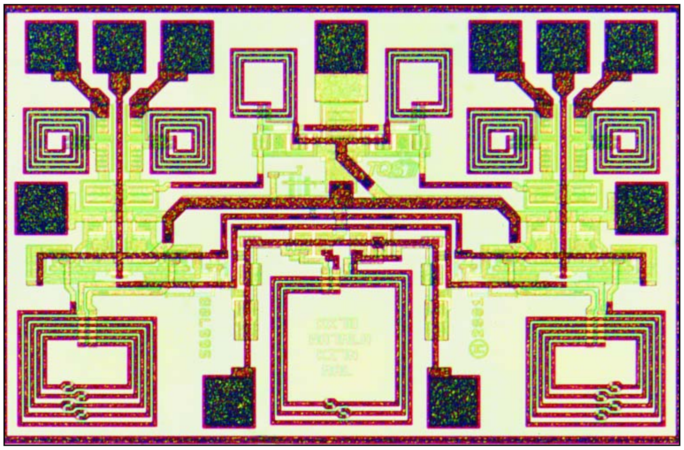

Figure 5 · Die photograph of the IQ Star Mixer.

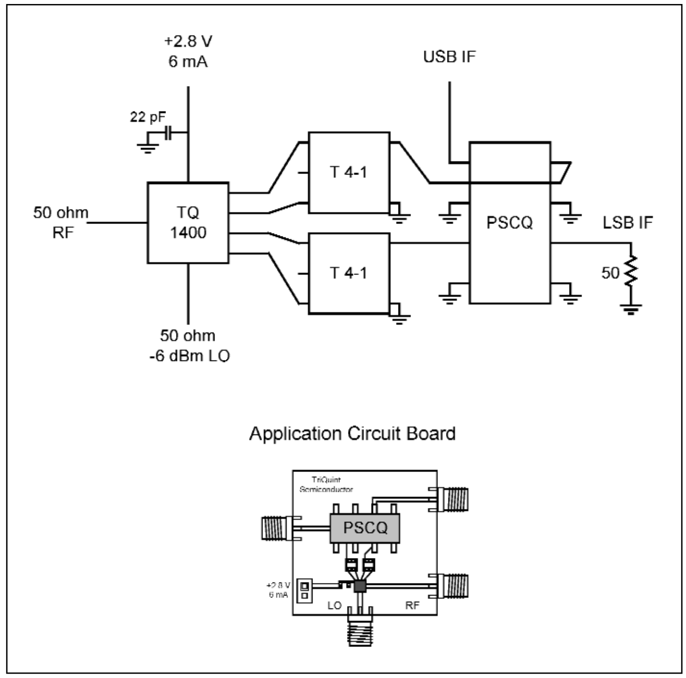

Figure 6 · Typical appplication circuit for the I-Q mixer.

LO leakage from the I mixer is shifted 90 degrees from the Q mixer LO. If the I mixer LO leakage is presented to the RF port of the Q mixer, the LO phase noise is downconverted to baseband. Isolating the I and Q mixer RF ports suppresses this demodulated phase noise.

Fabrication

A family of mixers was designed and built for 20 percent bandwidths with center frequencies from 900 MHz through 2400 MHz. Figure 5 is a die photograph of the 2 GHz IQ Star Mixer. Die dimensions are 0.9 mm x 1.3 mm. The mixer is fabricated on TriQuint's TQTRx GaAs process, using 0.6 micron D and E MESFETs. The TQTRx process has 50 ohm per square nichrome resistors, MIM capacitors, and 3 additional layers of interconnecting gold metal with thicknesses of 2 microns, 4 microns and 6 microns. Inductors and tuned transformers fabricated using the thick gold metal layers exhibit losses similar to small discrete chip components. For example, the small 5.4 nH inductors used in the 2 GHz Wilkinson Splitter have a typical Q of around 30. The symmetrical layout is necessary, as electromagnetic coupling between the LO drive circuitry of the I and Q mixer sections is the limiting factor on phase accuracy.

Performance

Performance of the mixer family was measured in a 50 ohm system with a passive IF combiner consisting of a pair of Mini Circuits T4:1 transformers and a Mini Circuits PSCQ 21.4 quadrature hybrid, as shown in Figure 6. The LO drive level is minus 6 dBm, and total operating current is 6 mA from a single 2.8 volt DC supply. Total conversion loss, including circuit board and IF component losses, is approximately 7.5 dB at 900 MHz and 8.5 dB for the 2400 MHz mixer. Input 3rd order intercept is between +18 and +20 dBm for all versions. Measured SSB noise figure with the 21.4 MHz passive IF combiner is within 1 dB of conversion loss. Typical LO leakage at the RF port is –30 dBm. Input 2nd order intercept is typically +44 dBm. 2nd order intercept is limited by mixer balance and LO leakage at the RF input port, which may both be improved by adding DC offset adjustments at the IF ports.

The I-Q mixer family was also measured using the active analog baseband combiner circuitry described in chapter 9 of ref. [6]. SSB noise figure with a 300 to 3000 Hz IF including the active audio input circuit noise is between 14 and 18 dB, which is similar to SSB systems at HF using diode ring mixers. This represents an excess $1/f$ noise of approximately 6 dB at 1 kHz. With the excellent phase and amplitude match of the integrated I-Q mixer and a single baseband amplitude and phase trim, more than 40 dB of opposite sideband suppression is easily obtained across both the 300 to 3000 Hz channel bandwidth and a 5 percent RF bandwidth. The +18 dBm 3rd order input intercept permits significant LNA gain to be used ahead of the mixer to trade intercept for noise figure. A 2 stage LNA with high S_{12} is recommended to reduce the level of LO leakage at the receiver antenna input. A prototype receiver front-end with a two stage LNA and I-Q mixer integrated on the same GaAs die exhibited a SSB noise figure of 1.8 dB and input 3rd order intercept of minus 6 dBm.

Application Circuitry

The precision amplitude and phase matching obtained when all of the critical microwave components are integrated is a fringe benefit—the primary reason for integrating the entire microwave I-Q down converter is to greatly simplify the application circuit. Application circuits, as seen in Figure 6, are almost as simple as block diagrams. There are numerous choices for LNAs and low power linear amplifiers with internal 50 ohm input and output match and only a single off-chip bypass capacitor. The integrated IQ Star Mixer also has 50 ohm LO and RF ports, only one bypass capacitor, and 200 ohm balanced I and Q IF ports. Suitable interface circuitry, using opamps or audio transformers, is described in chapter 9 of ref. [6], along with photographs of complete direct conversion receiver and transmitter systems.

The ease of using inexpensive I-Q down converters and up converters for the microwave portion of simple radio links makes them attractive for soft radio applications where modulation techniques and bandwidths are handled at baseband using DSP and software. This approach is being pursued at Oregon State University for their TekBot program, a platform for engineering education.

Acknowledgements.

This work evolved from fundamental mixer studies and passive FET balanced mixer experiments with Wes Hayward and Dennis Criss for cell phone ASIC applications. All of the PC board layouts for the application circuitry and some of the measurements were done by TriQuint Principal Technician Terry White. This work was performed in the TriQuint Semiconductor Advanced Development Group.

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