CMOS Front End Components for Micropower RF Wireless Systems

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1. ABSTRACT

New applications have recently appeared for a low power, low cost, "embedded radio". These wireless interfaces for handheld mobile nodes and Wireless Integrated Network Sensors (WINS) must provide spread spectrum signaling for multi-user operation at 902-928 MHz. Cost considerations motivate the development of complete micropower CMOS RF systems operating at previously unexplored low power levels. Micropower CMOS VCO and mixer circuits, developed for these emerging narrow-band communication systems, are reported here. Design methods combining high-Q inductors and weak inversion MOSFET operation enable the lowest reported operating power for RF front end components including a voltage-controlled oscillator (VCO) and mixer operating at frequencies of 400 MHz – 1 GHz. In addition, the VCO, by virtue of its high-Q inductive components, displays the lowest reported phase noise for 1 GHz CMOS VCO systems for any power dissipation.

2. INTRODUCTION

A low system cost wireless technology would provide mobility for handheld, networked computing, access between mobile systems and other information appliances, and network access to distributed embedded processors and sensors[2]. At this time, development effort is focused on an integrated, embedded radio modem technology. Low cost enables horizontal market applications. Most of these new applications are power constrained by battery peak power capability, and energy constrained by battery capacity, operating time, and battery cost.

A typical application for the embedded radio is the networking of office, factory, and residential appliances for remote sensing and control of the entire enterprise. Communication range for these applications is short, 5 – 15 m, and may exploit multihop networking. Further, the nature of distributed sensing and embedded control implies that control signals can be supported with low peak and average data rates. However, the presence of many nodes in an environment requires spread spectrum communication, operating in the unlicensed ISM bands centered near 0.9 or 2.4 GHz. Low power constraints dictate the choice of a frequency-hopped spread spectrum architecture with network power control.

The choice between bipolar or CMOS technologies for implementation of the embedded radio, favors bipolar systems due to the proven capabilities of low power bipolar RF circuits[7]. However, cost constraints dictate the choice of CMOS circuits and systems.

The embedded radio transceiver must operate with new CMOS circuits operating at lower peak and average power than any previous spread spectrum RF transceiver system. This paper reports advances in micropower RF circuits implemented with MOSFET transistors biased in the weak inversion region[2]. This is the first report of a tunable local oscillator operating at center frequencies between 400 MHz and 1 GHz and power as low as 300 μW.

The sharp reduction in power requirements for the local oscillator is the result of high-Q inductor integration. As will be shown, high-Q inductors provide both power and phase noise reduction. The cost and performance advantages of off-chip inductors will be discussed. These high-Q inductors have been implemented successfully in off-chip components as either low cost discrete components, in board level passive circuit patterns, or integrated into low temperature co-fired ceramic substrates. As will be described, in each case, cost of this off-chip integration is balanced by the cost savings in silicon area for the large on-chip inductors and the reduction in required battery cost and increased system operating life.

Most importantly, the combination of weak inversion CMOS transistor operation and high-Q passive components provides the lowest reported power dissipation for RF CMOS components. In addition, the contribution of high-Q characteristics provides the lowest reported phase noise for any CMOS oscillator at any power dissipation level. [see the review of Reference 3]

Finally, a new weak inversion, CMOS mixer is reported. For direct conversion operation, this device shows 12 dB voltage gain for 928 MHz RF and LO input signal and 45 μW core power dissipation. While low power operation degrades noise figure, intermodulation distortion and compression characteristics compare favorably with the properties of all reported CMOS mixers.

In summary, in contrast to the previously reported work[2], this paper describes micropower CMOS oscillators with tunability over a 10 percent range and record low phase noise levels for CMOS oscillators. In addition, the essential capabilities for micropower mixers have been demonstrated. Thus, the primary components for the embedded radio modem have been demonstrated in low cost, digital CMOS technology.

3. MICROPOWER CMOS VCO

The primary challenge for micropower transceiver development is that circuits must be optimized for operation at a total power dissipation at least a factor of 10 times less than conventional CMOS RF systems[1,3,5,6]. Dramatic power reduction may be obtained by developing circuits based on the weak inversion operation. However, design methods must be developed to mitigate the effects of low gain and high noise associated with micropower operation. By introducing high-Q inductive elements, it is demonstrated here that adequate gain and low noise are achievable. Two primary transceiver components, a VCO and mixer, are presented below.

First, considering the critical phase noise associated with oscillator operation. As demonstrated by Leeson's theory for LC oscillator phase noise power, S_ϕ, at frequency offset of Δw away from the carrier at frequency ω_0 with an input noise power, S_{noise}[4], and LC tank quality factor, Q, phase noise power is:

$$S_f \propto \frac{1}{Q^2}\left(\frac{w_0}{\Delta w}\right)^2 S_{noise}$$

Now, phase noise power, S_{noise}, at the transistor input, increases with decreasing drain current and power dissipation due to the resulting decrease in transistor transconductance. Thus, conventional circuits would provide degraded performance at the desired micropower level. However, for an LC resonator oscillator, phase noise may be sharply reduced by increasing Q. In addition, micropower operation of an LC-tank oscillator requires that loop gain (the product of amplifier transconductance and LC resonator gain, Q) be unity in steady state. Thus, since gain scales with drain current and power dissipation, a minimum drain current exists at which a MOSFET oscillator amplifier element supplies adequate gain for oscillation. Therefore, by increasing Q, MOSFET gain requirements, and therefore power dissipation requirements, are reduced.

Several investigators have demonstrated on-chip LC circuits for broad-band RF systems[5,6]. Integrated on-chip passive inductors provide Q values of typically 3 - 5 at 1 GHz in standard CMOS technologies. These Q values are limited by the conductor resistance and eddy current loss in the silicon substrate. On the other hand, off-chip inductors on low loss substrates deliver much higher Q values. For example, inductors incorporated in ceramic substrates (low temperature co-fired ceramic) offer low loss characteristics as well as packaging advantages[8]. It is important to note that the cost of off-chip inductors is mitigated by the removal of the large area on-chip passive inductors from the expensive submicron CMOS die area.

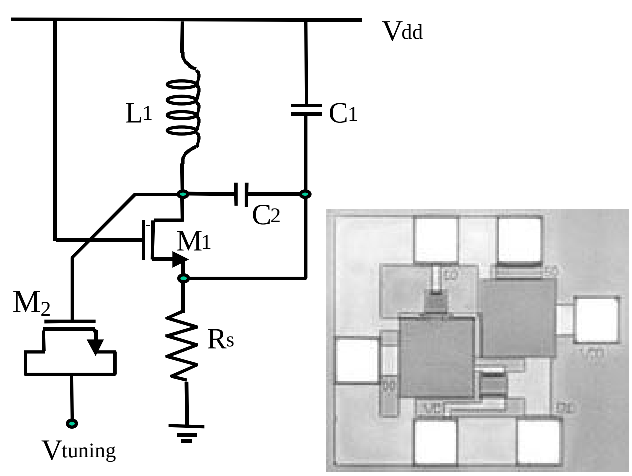

Figure 1 Micropower Colpitts voltage controlled oscillator (VCO) and chip photo.

Micropower oscillator performance was investigated using both single phase and dual phase oscillators implemented in 0.8μm HP CMOS26G technology. Figure 1 shows the single phase Colpitts oscillator, where R_s sets the drain current. A MOSFET varactor, M_1, provides tuning capability. Differential oscillators have also been fabricated. For both systems, frequency tuning is obtained through MOSFET varactors.

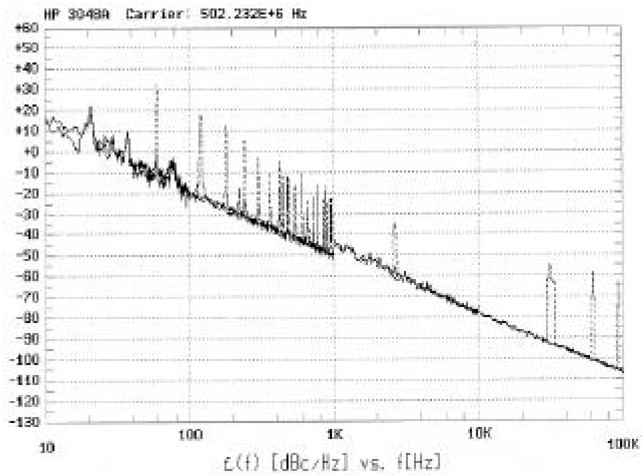

Figure 2. Measured phase noise spectra for the VCO of Figure 1. Phase noise at 100 kHz offset is -107 dBc/Hz at 690 µw power dissipation. Spurious spectral peaks in the data (primarily at multiples of the line frequency) are due to the high sensitivity HP 3048A phase noise analyzer apparatus.

The off-chip inductors employed in this example oscillator are loop inductors with inductance of 40 nH and Q values of over 200 as extracted by a network analyzer. Measurement of phase noise employs use of a weakly coupled coil (avoiding the need for 50-Ω buffer stages) to sample the oscillator output to the HP 3048A phase noise measurement system.

The VCO is designed for both direct-conversion and super-heterodyne architectures. A series of VCOs from 400 MHz to 1 GHz are implemented. Relative phase noise of less than –100 dBc/Hz is measured at 100 kHz offset frequency with power dissipation of 300 µW for Colpitts oscillators and 700 µW for dual-phase oscillators. One representative measurement result is shown in Figure 2 with phase noise of less than –107 dBc at 100kHz. Tuning range of 10% of oscillation frequency is obtained. These phase noise results, by virtue of the high-Q low loss tank, compare well with previously reported CMOS oscillators at any power, as described in the recent detailed review[3].

Besides discrete loop inductors, VCOs employing LTCC (Low temperature Co-fired Ceramic) inductors are also under development. Figure 3 shows a sample LTCC board layout, which includes high-Q, low loss passive components, pick-up coils, pads, and chip carrier all in the same common substrate. With the low-loss, multilayer capability of LTCC, the complete CMOS micropower RF front-end system can be built into a small board.

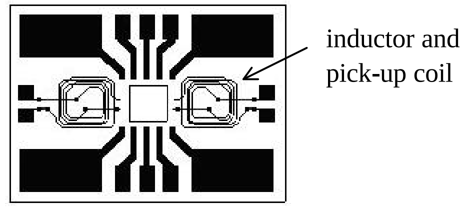

Figure 3. An example of low temperature co-fired ceramic (LTCC) board layout.

4. MICROPOWER CMOS MIXER

Micropower mixer design must balance the demands between conversion gain, linearity, noise, and power dissipation. In addition, mixer design should exploit the narrow bandwidth of WINS communication systems to obtain low power operation. This narrow bandwidth may be achieved for a low frequency (zero-IF, direct conversion) output or a high frequency output. For a low frequency output, the bandwidth of the mixer output stage is required to only accommodate the low bit rate signaling (10 kbps) required. This mixer will naturally reject the undesired high frequency mixer output due to its narrowband properties. However, high frequency, narrowband output may also be obtained by tuning the mixer output to IF with a high-Q LC tank circuit.

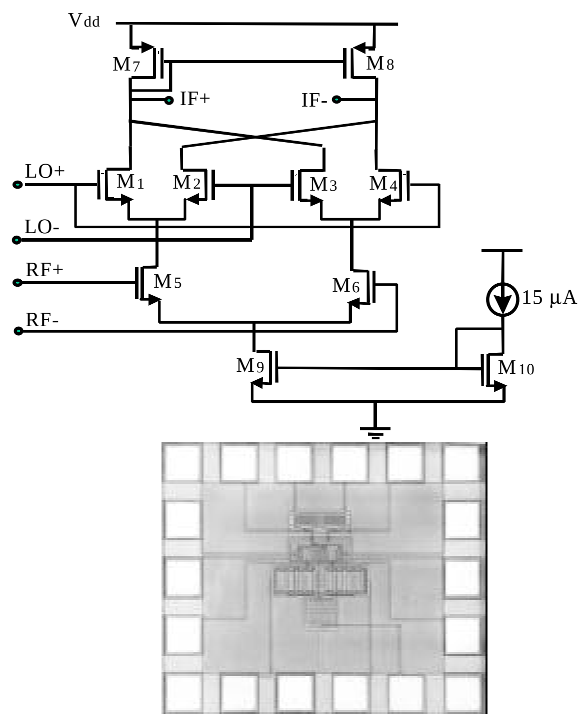

Figure 4. Micropower Gilbert cell mixer and chip photo. The mixer core, with transistors operating in weak inversion, draws 15µA from its 3V supply.

The double-balanced Gilbert cell mixer is chosen for its fully differential structure and good LO-IF isolation. The circuit diagram for the zero-IF micropower down-conversion mixer is shown in Figure 4. By adding a high-Q LC tank circuit at the mixer output, the same circuit is adapted to perform high-IF down-conversion.

A direct (zero-IF) down-conversion mixer has been implemented in HP CMOS26G 0.8 μm technology. The mixer core consumes only 15 μA at 3 V supply. Figure 5 shows an example measurement of intermodulation distortion for input frequencies at RF of 928.000MHz, 927.999MHz, (-25dBm) and LO at 928.005 MHz (-11 dBm). Complete measurements of gain compression are shown in Figure 6 and intermodulation distortion in Figure 7. Excellent performance is obtained with 12 dB voltage conversion gain, input 1dB compression point of -12 dBm, and IIP_3 level of -3dBm measured with LO power of -11 dBm. It should be noted that the measure of power corresponds to power into an effective 50 Ω load. Actual circuit implementation and testing involves only high impedance loads to permit low power operation.

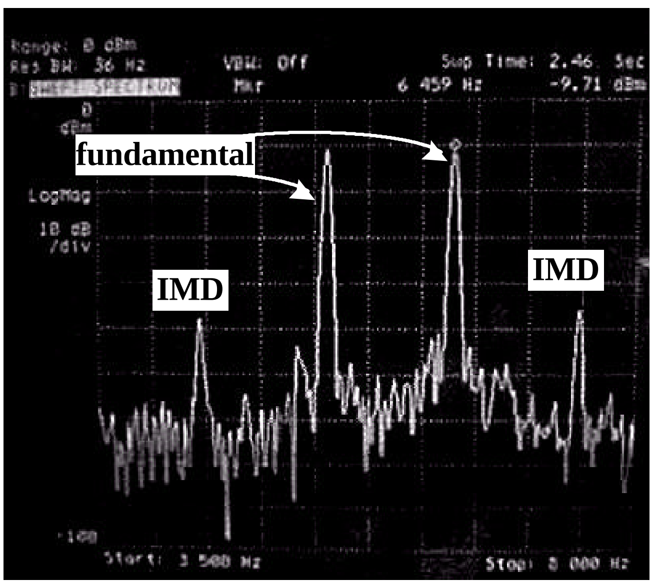

Figure 5. Measured mixer response showing two-tone, third-order intermodulation distortion. Input RF signals are at 928.000, 927.999, and input LO signal at 928.005 MHz. The small intermodulation distortion appears at 4 and 7 kHz with fundamental output product signals at 5 and 6 kHz. The fundamental and intermodulation products are labeled.

CMOS mixers generally display better linearity performance than BJT mixers. This is due to the fact that MOS drain current depends quadratically on gate-source voltage, to a first-order approximation, while bipolar current depends exponentially on the base-emitter voltage. It is thus expected that the micropower mixer operating in weak inversion will show increased intermodulation distortion compared to strong inversion CMOS mixer circuits. However, with proper transistors sizing and some penalty on noise performance, good linearity is achieved, as demonstrated in our work.

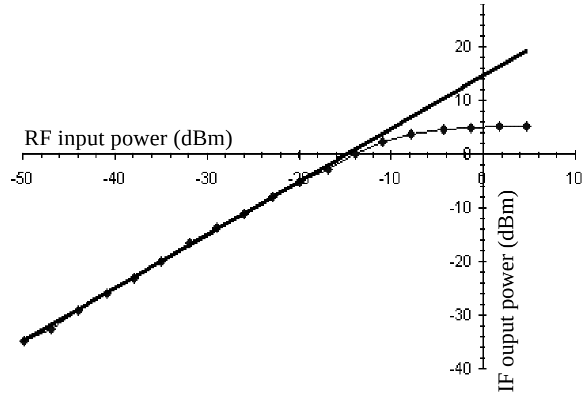

Figure 6. Measured 1-dB compression for the mixer of Figure 4. (Measured at LO power of - 11 dBm at an IF frequency 5 kHz)

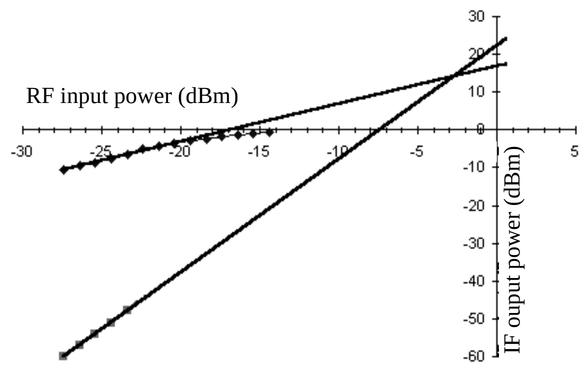

Figure 7. Measured two-tone, third-order intermodulation distortion for the mixer of Figure 4. The IIP_3 point (intersection of fundamental and third-order products) occurs at an input RF power of -3dBm.

5. PASSIVE COMPONENT INTEGRATION FOR LOW POWER

The RF circuit designer must choose between on-chip and off-chip passive component integration. For low power implementation, the chosen method must provide methods to recover high performance from low power circuits reported here. The results above show that the proper choice for power and performance is for off-chip integration. Off-chip integration may first appear to present a cost disadvantage over on-chip integration. However, it is important to discuss the potential cost advantages of off-chip component integration.

Now, passive inductors included on the CMOS die ("on-chip") suffer from substrate eddy current losses, reduced self-resonant frequency, and the possible requirements for non-standard wafer processing. For high performance, high power dissipation, broad band radio modems, low-Q circuits are compatible (or are required) for broad band fast-hopping, and high process gain systems. In contrast, for narrowband embedded radio modems, the design choice must be optimized for low bit rate and should exploit high-Q circuits.

The high-Q circuits reported here have been implemented successfully with off-chip components as either low cost discrete components, in board level passive circuit patterns, or integrated into low temperature co-fired ceramic substrates. The use of bond pads carrying a ground shield between pad and substrate isolates the pads from the lossy substrate.

For each integration method, cost of this off-chip integration is balanced by several issues: 1) Removing the passive components from the lossy silicon substrate drastically reduces power requirements to obtain specified performance. Therefore the high system cost associated with batteries and their prohibitive replacement cost is reduced. 2) Removing large area passive components from the chip onto the low real estate cost substrate, reduces the high cost associated with the large silicon area required for the large inductors. 3) Eliminating the requirements for non-standard CMOS technology modification required for inductors reduces development time. Finally, all RF CMOS integration methods will rely on packaging of the complete die or chipset. For packaging that relies on multichip modules, ceramic substrates, chip-on-board, and other methods, the low loss inductors reported here may be integrated with package. Thus, the incremental cost for adding low loss RF passives may be minimized.

6. CONCLUSIONS

Wireless embedded processors and microcontrollers, distributed networked sensors, patient monitoring systems, compact, handheld, mobile computers creates and other applications all require support for low bit rate wireless messaging over short range links. Micropower RF CMOS circuits and systems may provide the required RF front-end components. A new design methodology combining weak-inversion MOSFET operation loaded with high-Q inductors enables high performance, micropower CMOS transceiver components. This design method has yielded the lowest reported power for oscillators and mixers and the lowest reported CMOS oscillator phase noise. The successful demonstration of micropower CMOS RF oscillators and mixers demonstrates feasibility of a complete micropower CMOS RF front-end system for narrow-band wireless communication systems.

7. ACKNOWLEDGMENTS

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