MICROPOWER CMOS RF COMPONENTS FOR DISTRIBUTED WIRELESS SENSORS

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Abstract

A wide range of 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. Conventional low power RF systems have been implemented in bipolar technology. However, cost considerations motivate the development of complete micropower CMOS RF circuits and 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 mixer and voltage-controlled oscillator (VCO) operating at frequencies of 400-900 MHz. In addition, the VCO, by virtue of its high-Q inductive components, displays the lowest reported phase noise for 1GHz CMOS VCO systems for any power dissipation.

I. 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.[1] 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 will require 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 circuit technologies for implementation of the embedded radio, favors bipolar systems due to the proven capabilities of low power bipolar RF circuits.[2] 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 operating region.[1] This is the first report of a tunable local oscillator operating at center frequencies between 400 and 900 MHz 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.

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Most importantly, the combination of weak inversion CMOS transistor operation and high-Q passive and active 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 with 45 μW core power dissipation. While low power operation degrades noise figure, intermodulation distortion and compression characteristics compare favorably with other reported CMOS mixers.

In summary, in contrast to the previously reported work,[1] 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.

II. Micropower CMOS RF Voltage Controlled Oscillator (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.[3-6] Dramatic power reduction may be obtained by developing circuits based on MOSFETs operating in the weak-inversion region. 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, we may consider 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 $\delta\omega$ away from the carrier at frequency ω with an input noise power, S_{noise}[7], and LC tank quality factor, Q, phase noise power is:

$$S_\phi \propto \frac{1}{Q^2}\left(\frac{f}{\Delta f}\right)^2 S_{noise}$$

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.[4,6] 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.

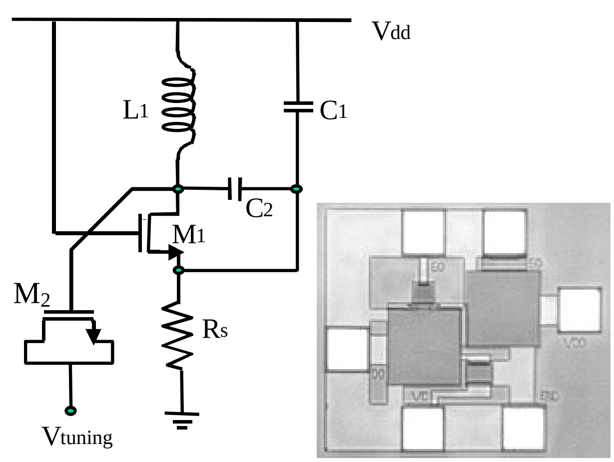

Figure 1. Micropower Colpitts voltage controlled oscillator (VCO) and chip photo.

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_2, provides tuning capability. Differential oscillators have also been fabricated. For both systems, frequency tuning is obtained through MOSFET varactors.

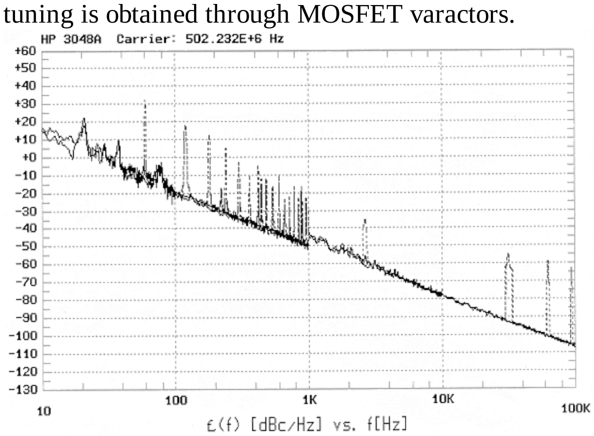

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Figure 2. Measured phase noise spectra for the VCO of Figure 1. Phase noise at 100 kHz offset is -107 dBc/Hz at 690 μw power dissipation. Spurious spectral peaks in the data (primarily at multiples of the line frequency) are due to the high sensitivity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

The off-chip inductors employed in this 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 oscillation output to an 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 900 MHz 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 100 kHz. 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]

It is important to note that the low phase noise values obtained here, relies on the presence of high-Q inductors in the oscillator circuit. Specifically, the large "1/f" noise observed for the 0.5μ CMOS process dominates input referred voltage noise at the oscillator transistors. Further 1/f noise is nearly independent of drain current (power dissipation).[9] Therefore, design for low phase noise in CMOS oscillators may focus on introduction of high-Q elements, rather than by power.

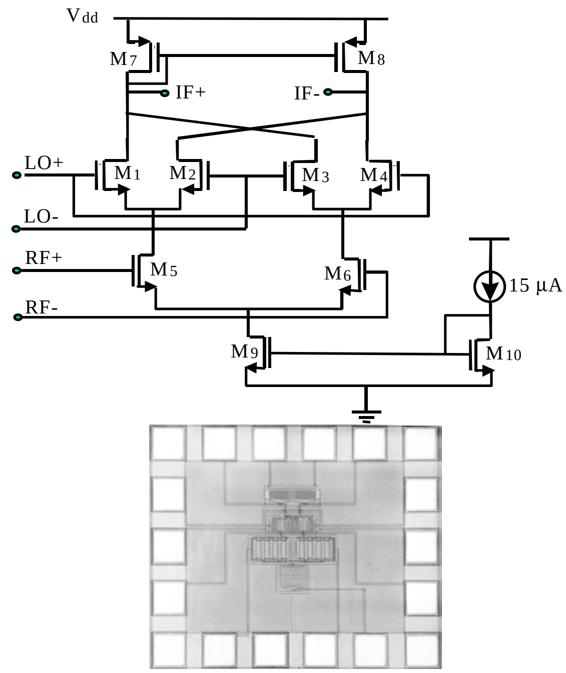

Figure 3. Micropower Gilbert Cell mixer and chip photo. The mixer core, with transistors operating in weak inversion, draws 15μA from its 3V supply.

III. 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.

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 Fig. 3. 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 0.8 µm HP CMOS26G technology. The mixer core consumes only 15 µA at 3 V supply. 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. Fig. 4 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). 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.

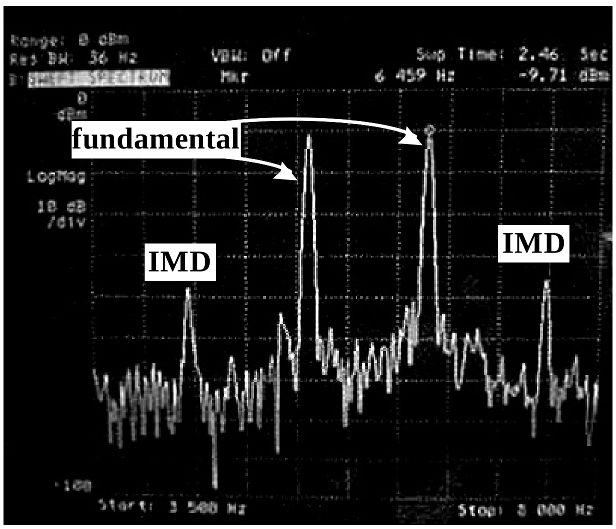

Figure 4. Measured mixer response showing two-tone, third-order intermodulation distortion. Input RF signals are at 928.000, 927.999, and input LO signal at 928.005 MHz. The small intermodulation distortion appears at 4 and 7 kHz with fundamental output product signals at 5 and 6 kHz. The fundamental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

IV. 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.

V. Acknowledgments

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