A NOVEL RF TO BASEBAND MONOLITHIC MICROWAVE RECEIVER WITH ON-CHIP TUNING

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Abstract **- A novel single-chip monolithic microwave receiver on Silicon with integrated high Q inductors and laser-trimmable capacitors and resistors is presented. All functions, including some elementary mixed signal circuitry, necessary to demodulate a 1.5 GHz signal and convert it to baseband digital data are described.**

Introduction

Size requirements demanded in many of today's applications require innovative methods in design, fabrication, and testing. This was especially true of a completely monolithic microwave receiver that includes all of the functions necessary to take a modulated RF carrier and produce CMOS level baseband data while operating from a single 5 Volt source.

The task of integrating functions such as power supply regulation, RF amplification, demodulation, and baseband processing is very complicated with respect to simulation. Process variations must be accounted for in the design, and innovative technologies, such as on-chip tuning, may be required. Furthermore, with all of the functions on a single chip, EM coupling and other interactions must be minimized by both passive and active means.

Chip Architecture

The radio frequency integrated circuit (RFIC) being presented contains all of the functions necessary to demodulate an L-band signal and produce baseband digital data (see Figure 1). The tunable RF amplifier operates in the L-band frequency range (1 to 2 GHz) and was designed as an ultra-high gain (approximately 38 to 43 dB) pre-amplifier. The pulse modulated RF signal is then demodulated by the proprietary tunable synchronous oscillator/demodulator. Frequency tuning of this oscillator is available through a 5-bit frequency control digital to analog converter (DAC). The demodulated baseband analog signal (10 kbps) is then amplified with approximately 53 dB of gain, offset corrected, and passed through a comparator for CMOS scaling, producing inverted and non-inverted outputs. An on-chip regulator provides all of the required voltages from a single 5 Volt input. The regulator design provides temperature compensated outputs and has excellent power line rejection qualities to accommodate noisy 5 Volt inputs without requiring large de-coupling capacitors.

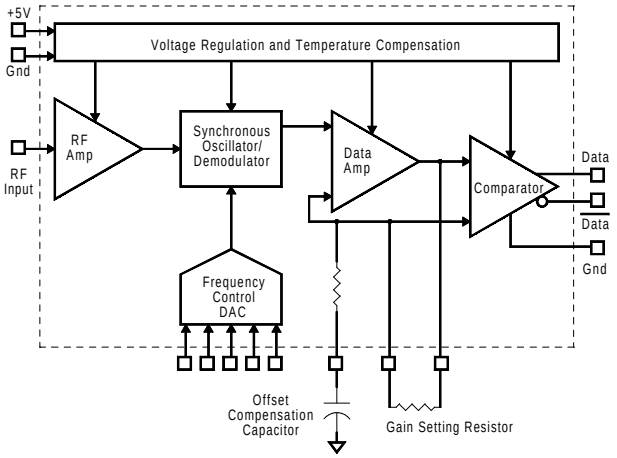

Figure 1. Block Diagram of Receiver Chip.

The chip size, 2.4 mm by 3.8 mm (95 mil by 150 mil), was mostly driven by the requirement for input/output pads necessary for the extensive testing to characterize this novel chip (see Figure 2). The excess chip area not used for the essential circuits (approximately one third of the total area) is used for additional power supply de-coupling capacitors.

Passive Components

This RFIC was fabricated on a complimentary bipolar process (CBIC-V2) that produces 10 Volt NPN transistors with f_t's of 10 GHz and 10 Volt PNPs with f_t's of 4.5 GHz [1]. This IC process utilizes several types of resistor and capacitor structures, and at the time this chip was being designed (not coincidentally), the process was just introducing high Q inductors.

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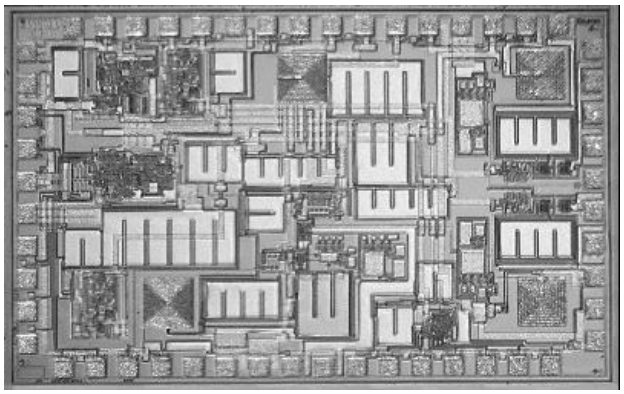

Figure 2. Monolithic Microwave Receiver RFIC

Laser-Trimmable Capacitors and Resistors

The RF amplifier and synchronous oscillator that will be discuss later both contain laser-trimmable components that allow correction for any variances that may occur due to IC processing. Laser-trimmable bias resistors adjust for DC characteristics in the resistors and transistors, while laser-trimmable capacitors adjust for high frequency reactances. (One important clue pointing toward the necessity of laser trimming was the foundry guidelines stating that capacitor values could vary by as much as +/- 35% from wafer to wafer.)

Laser-trimmable resistors were designed by determining a minimum resistance value to create a core resistor with additional resistors of varying values placed in series to create the range of required total values. Metal lines, 4 μm wide, were placed in shunt across each additional resistor, thereby shorting each one out of the circuit. Therefore, if further bias resistance were required in the circuit, the appropriate line could be laser trimmed (cut) to increase the total resistance.

Similarly, trimmable capacitors were designed by determining a range of capacitances. These capacitors functioned as elements in RF tuning networks, thereby becoming critical components with respect to the microwave frequencies. The minimum value determined the size of the core capacitor, while other values adding up to the total created the maximum value (a total capacitance value as high as 1.2 pF). These other values of "trim" capacitors (some as small as 25 fF) were placed in parallel with the core capacitor via 4 μm wide lines; therefore, by laser trimming one of the lines, the total capacitance was decreased. A picture of one of the laser-trimmable capacitors can be seen in Figure 3.

High Q Inductors

High quality integrated inductors are typically difficult to achieve on Si substrates due to the relatively high conductivity of the substrates (especially when compared to GaAs). Yet, they are highly desirable to have on a chip that requires inductive reactances because they can greatly reduce the size of a circuit and increase producibility and reliability. Recent advances in Si technology have yielded integrated inductors with Qs as high as 12 at L- and S-band frequencies [2]. Using this same technology, four square spiral inductors of varying values and measuring 300 μm on a side were designed into the chip. Shown in Figure 4 is a picture of one of the inductors used in the RF amplifier as part of a tuning circuit. The inductor measures approximately 8.5 nH and has a peak Q of 7.5. Measured inductor s-parameters from test wafers allowed SPICE models to be derived [3] and used in simulations during the design of the active circuits.

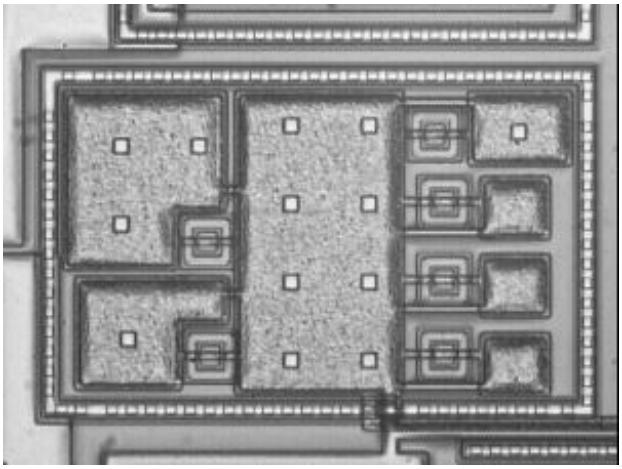

Figure 3. Picture of Laser-Trimmable Capacitor.

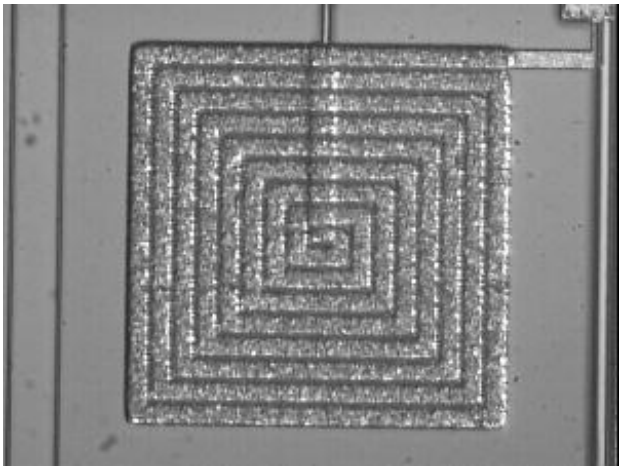

Figure 4. Picture of High Q Silicon Inductor.

Active Circuits

This section is intended to describe the different functions represented in the block diagram of Figure 1 and how they interact with each other to create a complete monolithic receiver.

Power Supply Regulator

The term "power supply regulator" describes the circuitry that performs the different voltage regulation functions on the RFIC and then distributes those regulated voltages to the other circuits. This circuit begins by taking a 5 V source and pre-regulating it to 3.5 V, which is then further down-regulated to 2.0 V. The regulation circuitry is based on a band gap reference that has been optimized for this particular IC process [4], and consequently produces a very good power supply rejection ratio (PSRR). Furthermore, the band gap circuit provides first order temperature compensation, thus stabilizing other circuitry on the chip with respect to temperature.

RF Amplifiers

The design of this RFIC actually has two versions (Chip A and Chip B) that are defined by the RF amplifiers employed on each respective chip. The fabrication of two chip designs was done as part of a risk management plan in case an amplifier did not perform as designed. The first amplifier (referred to as "Amp A" and found on Chip A) was a multistage design that relied on active impedance matching between two of the high gain stages. The other amplifier, Amp B on Chip B, employed a traditional approach by cascading two cascode amplifiers together with passive impedance matching. Each version of RF amplifier utilized two of the high Q inductors and several of the laser-tunable capacitors and resistors.

Gain performance of both amplifiers compared well with simulations. Amp A gain, while biased at 11 mA, peaks at 43 dB at the center frequency (see Figure 5), while Amp B provides slightly less gain of about 38 dB and consuming 16 mA (see Figure 6). Noise figures for the amplifiers measured 7 dB and 3.5 dB at their minimums for amplifiers A and B respectively.

Demodulation Circuitry

The demodulation circuitry is based on a novel concept requiring only a handful of devices. The circuit is an oscillator consisting of two transistors and several passive components, including inductors and laser-tunable capacitors and resistors. This oscillator synchronously "locks" to the RF signal amplified by one of the high gain RF amplifiers previously described, and strips off the baseband data directly. In essence, the oscillator performs the functions of a local oscillator, mixer, IF amplifier, IF filter, and demodulator all in one step. This particular circuit is a major contributor in keeping the size of this RFIC small, where a conventional heterodyne modulation process would be much larger.

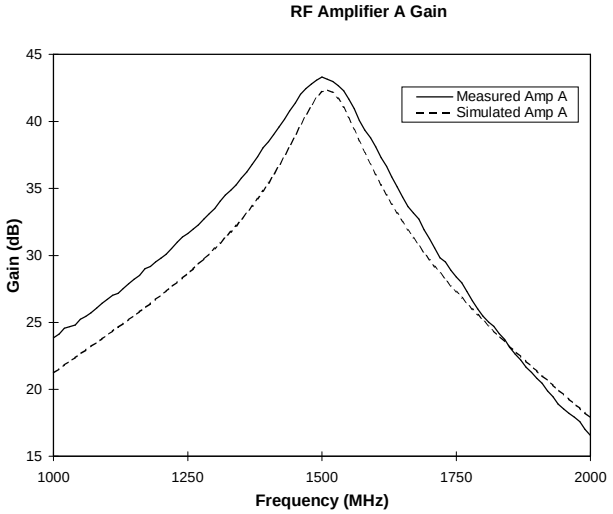

Figure 5. Gain of Amp A (simulated and measured).

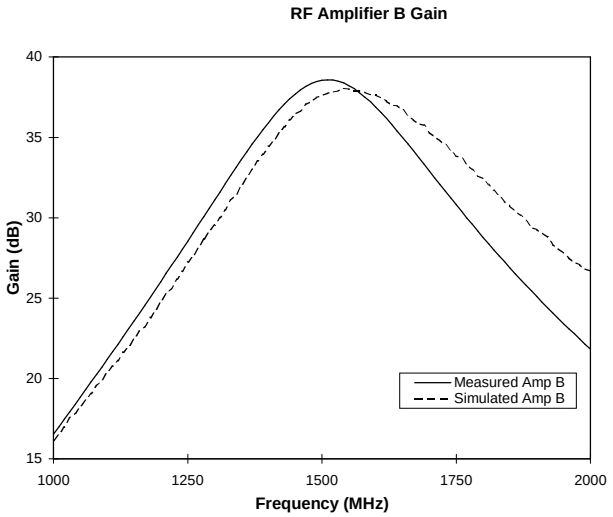

Figure 6. Gain of Amp B (simulated and measured).

Frequency Control DAC

A current mode 5- bit DAC was provided on the RFIC to sink or source a current into the oscillator circuit used for the demodulation process. By controlling currents of a few microamperes, it is possible to adjust the center frequency of the oscillator by approximately +/- 15 MHz. The DAC is intended as a static adjustment, and is implemented by tying open emitters of each DAC bit to ground to activate that particular bit.

Baseband Processing

The baseband data signal provided by the demodulation circuit is an analog signal with an amplitude that can be as low as tens of microvolts. A data amplifier on the chip boosts this signal with approximately 53 dB of gain, thus providing a signal that can be passed to the comparator. The power supply rejection of the voltage regulator previously described, and a novel biasing scheme that assists with the rejection in the amplifier and comparator [5], are very important. This rejection reduces any noise that may be passed on to the data amplifier and cause bit errors at the comparator output. Isolation from the RF circuitry was also required, and was accomplished by providing a separate band gap reference for the relatively high current RF amplifiers. (The data amplifier and comparator operate with bias currents in the microamperes.)

The data amplifier does require two off-chip components. The first is an offset correcting capacitor of about 0.2 μF (definitely too large too integrate on the IC), which allows the baseband circuitry to be DC coupled. If not used, AC coupling would be required, forcing multiple and much larger capacitors to be used. The other part required off chip is a 1.5 MΩ feedback resistor that was considered a risk, with respect to yield, to put on chip.

Shown in Figure 7 is an oscilloscope picture of the data amplifier output and the non-inverted comparator output. The signal being injected into the receiver had a power level of -95 dBm.

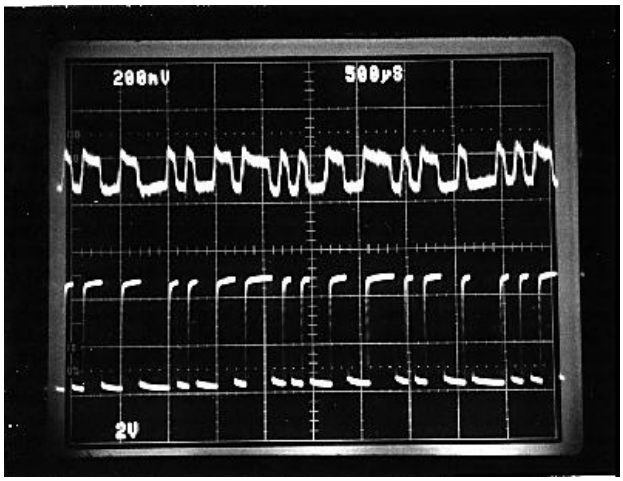

Figure 7. Oscilloscope Picture of Demodulated Signal (-95 dBm). The top trace is the data amplifier output and the bottom trace is the comparator output.

Performance Of Entire Integrated Chip

The total chip performance allows the circuit to demodulate an L-band pulse modulated signal that has a baseband data rate of 10 kbps. Measured sensitivity of this chip has yielded bit-error-rates (BER) of 10^{-5} for input power levels as low as -95 dBm. Temperature drift of the receiver is less than 50 ppm over a range of 0 to 70 °C. This low drift rate can be attributed not only to the temperature compensation found in the voltage regulator, but to the fact that the receiver is entirely integrated.

The laser-trimmable capacitors and resistors allow the RF amplifier and oscillator to be tuned in frequency by as much as 15%, and in the case of the oscillator, within 0.1% of the target frequency. The laser trimming is an excellent option that allows corrections to be made for variations due to IC processing. Furthermore, receivers from the same wafer lot can be tuned to different frequencies over a relatively wide band, thus increasing their application.

Summary

A laser-tunable monolithic microwave receiver has been presented that operates in the L-band frequency range. The entire demodulation process and supporting circuitry that allows a receiver to detect a low level RF signal and produce baseband data, were also reviewed. The two critical components that made this receiver realizable in the current form-factor are the integrated inductors and laser trimmable components.

References

[1] AT&T Microelectronics, *CBIC-V2 Product Development Guide*, AT&T, 1993.

[2] K. B. Ashby, I. A. Koullias, W. C. Finley, J. J. Bastek, and S. Moinian, "High Q Inductors for Wireless Applications in a Complementary Silicon Bipolar Process," *IEEE Journal of Solid-State Circuits*, vol. 31, no. 1, pp. 4 - 9, Jan. 1996.

[3] M. A. Wyatt, "Simple Technique Models Silicon Integrated Inductors," *Microwaves & RF*, pp. 67 - 68, Nov. 1995.

[4] AT&T, "Mixed Signals, Subs and Cells: A Low-Voltage, Low-Power Band Gap Reference for CBIC-V2," *The Bipolar Foundry*, pp. 9 - 11, Fall/Winter 1993.

[5] M. A. Wyatt, "Peaking Current Source Has High Rejection," *EDN*, pp. 145 - 148, Feb. 15, 1996.