RF Integrated Circuits

Introduction and Motivation

The recent explosion in the radio frequency (RF) and wireless market has caught the semiconductor industry by surprise. The increasing demand for affordable mobile communications has introduced numerous challenges in the design of cellular and cordless telephones and pagers, and new prospects for wireless technology have motivated dramatic changes in the thought process behind deploying a communication system. Affordability and portability are the two principal requirements and features of wireless communications. This chapter will deal with RF transceivers and some important RF building blocks.

Prerequisites

Knowledge of semiconductors, MOS-physics, inductors etc.

Learning Outcomes

- Architecture of Various RF components which can be fabricated on chip
- Applications of these RF components.

Suggested Time

12 hours

Transceiver Architecture

An RF receiver is defined from the port connected to a receiver antenna to an ADC, and an RF transmitter is defined from a DAC to the port connected to a transmitter antenna. The RF transmitter and receiver are usually formed not only by the RF devices and circuitry but also by intermediate frequency (IF) and analog base-band circuitry and devices.
The main blocks of an RF transceiver can be functionally classified into the following categories: frequency filters, amplifiers, frequency converters, modulators/demodulators, oscillators, synthesizers, ADC/DAC etc. At present most RF transceivers in wireless communications systems are using the superheterodyne architecture, invented in 1918. The figure below shows the block diagram of a superheterodyne full-duplex transceiver. The upper portion is the receiver and the lower portion corresponds to the transmitter. The duplexer and the synthesizer local oscillator (LO) operating at the ultrahigh frequency (UHF) are shared by both the transmitter and the receiver.

The duplexer consists of two band-pass filters with a common input port and two output ports. One filter is centered at receiver frequency band. It is used as the receiver preselection filter and to suppress transmission power leaking to the receiver. Another one is a transmitter filter that is employed to suppress out transmission band noise and spurious emissions. The duplexer is necessary for a
full duplex transceiver only if its receiver and transmitter use a common antenna. The UHF synthesizer not only provides the LO power to the RF converters in the receiver and the transmitter but also plays the role of channel tuning for the transceiver.

A super heterodyne receiver contains three sections - the RF, IF and BB. The RF section of the receiver includes part of the duplexer as the frequency preselect or, a low-noise amplifier (LNA), an RF band-pass filter (BPF), an RF amplifier as the preamplifier of the mixer and an RF-to-IF down-converter (mixer). The gain of the LNA can be stepped-controlled to cope with the receiver dynamic range. The RF BPF is usually a SAW filter. The function of this filter is to further suppress the transmission leakage, the image and other interference. The RF amplifier (RFA) or the preamplifier of the mixer provides enough gain to the receiver chain and thus the noise-figure of the down-converter and later stages has only slight influence to the receiver overall noise figure and sensitivity.

The down-converter performs the signal frequency translation from RF to IF. Following the down-converter is an IF amplifier (IFA) and then an IF BPF for channel selection and suppressing unwanted mixing products. The IF block provides most of the gain of the receiver and the IF variable gain amplifier (VGA) is formed by multiple amplifier stages. The I/Q demodulator is the second frequency converter, which down-converts the signal frequency form IF to BB. The demodulator contains two mixers, and it converts the IF signal into I and Q signals - two 90 degree phase-shifted BB signals. A low-pass filter (LPF) follows the mixer in I and Q channels to filter out the unwanted mixing products and to further suppress interferers. The filtered I and Q BB signals are amplified by BB amplifiers and then passed through ADC.

Similar to the super heterodyne receiver, a super heterodyne transmitter also consists of BB, IF and RF sections. I and Q digital BB signals that contain data are converted to the corresponding analog BB signals by the DAC in the I and Q channels of the transmitter BB section. After BB filtering, the I and Q BB signals are up-converted into IF signals, and the IF signal in the Q channel obtains 90 degrees more phase-shift than that in the I channel. The output of the I/Q modulator is the sum of the I and Q IF signals. The composite IF signal is amplified by the VGA, and then up-converted to an RF signal. The RF signal is further amplified by an RF VGA and then by a driver amplifier to a power level that is enough to drive the power amplifier (PA). An RF BPF (SAW filter) is inserted
between the driver and the PA to select the desired RF signal and suppress other mixing products generated by the RF up-converter. The PA boosts the desired RF signal to a power level that is high enough to make the transmission power at the antenna port being still greater than the minimum requirement after deducting the insertion losses of the isolator and the duplexer.

**Low Noise Amplifier**

Low-noise amplifier (LNA) is used to amplify very weak signals (for example, captured by an antenna). It is placed at the front-end of a radio receiver circuit. Using an LNA, the effect of noise from subsequent stages of the receive chain is reduced by the gain of the LNA, while the noise of the LNA itself is injected directly into the received signal. Thus, it is necessary for an LNA to boost the desired signal power while adding as little noise and distortion as possible, so that the retrieval of this signal is possible in the later stages in the system. A good LNA has a low noise figure (like 1 dB), a large enough gain (like 20 dB) and should have large enough intermodulation and compression point (IP3 and P1dB). The very low noise required of LNAs usually mandates the use of only one active device at the input without any (high frequency) resistive feedback. In order to provide sufficient gain while driving 50 Ω, some LNAs employ more than one stage.

A bipolar LNA is shown in the figure below, where the first stage utilizes a bond wire inductance $L_e = 1.5 \text{ nH}$ to degenerate the common-emitter amplifier, $Q_1$, without introducing additional noise. This technique both linearizes the LNA and makes it possible to achieve a 50 Ω input impedance. Bias voltages $V_{b1}$ and $V_{b2}$ and the low-frequency feedback amplifier $A_1$ are chosen to stabilize the gain against temperature and supply variations. The resistive feedback in the second stage improves the linearity and lowers the output impedance.
Another bipolar LNA designed to drive a 50 Ω load is depicted below. Employing negative feedback through a monolithic transformer to linearize the circuit, the LNA can operate with supply voltages as low as one $V_{BE}$. Interestingly, the transformer reduces the amplifier gain at both low and high frequencies, helping to stabilize the circuit. The external inductor $L_1$, and capacitor $C_1$, provide conjugate matching at the input.
Mixer

A mixer or frequency mixer is a nonlinear electrical circuit that creates new frequencies from two signals applied to it. In its most common application, two signals at frequencies $f_1$ and $f_2$ are applied to a mixer, and it produces new signals at the sum $f_1 + f_2$ and difference $f_1 - f_2$ of the original frequencies. Other frequency components may also be produced in a practical frequency mixer.

Mixers are widely used to shift signals from one frequency range to another, a process known as heterodyning, for convenience in transmission or further signal processing. For example, a key component of a superheterodyne receiver is a mixer used to move received signals to a common intermediate frequency. Frequency mixers are also used to modulate a carrier frequency in radio transmitters.

A double-balanced bipolar mixer designed in conjunction with the above LNA is shown below. Here, an on-chip transformer both operates as a single-ended to differential converter and provides input matching. The bias current of the switching quad is established by IEE, and capacitors $C_1 - C_3$ effect resonance at the primary and secondary transformers.
An electronic oscillator is an electronic circuit that produces a repetitive, oscillating electronic signal, often a sine wave or a square wave. The local oscillators used to drive down-conversion and up-conversion mixers are embedded in a synthesizer loop to achieve a precise frequency definition. Phase noise, sidebands (spurs), tuning range, and settling behavior of synthesizers are critical parameters in RF applications, creating severe trade-offs as the number of external components is reduced.
Most integrated RF oscillators are configured as a negative-$G_m$ stage with inductive load, as shown in the figure above. The idea is that an active circuit provides a negative resistance that cancels the finite loss in the inductors (and capacitors), thereby sustaining oscillation. While on-chip spiral inductors are attractive for higher levels of integration, various loss mechanisms limit the quality factor (Q) to approximately 4 in typical CMOS technologies. As depicted in the figure below, wire resistance and electric and magnetic coupling to the substrate contribute loss. Another important issue, particularly in CMOS circuits, is the up-conversion of $1/f$ noise to the vicinity of the carrier frequency.
In bipolar technologies, spiral inductors exhibit slightly higher Qs because the substrate is lightly doped, which results in lesser electric and magnetic coupling of the inductor to the substrate. The figure below shows a bipolar implementation incorporating monolithic inductors with a Q of approximately 9. Emitter followers are used in the loop to allow larger voltage swings at X and Y.

Loss mechanism in monolithic inductors: 
- a) wire resistance; 
- b) electric coupling to substrate; 
- c) magnetic coupling to substrate.

The figure below shows a CMOS VCO topology. Here, the transconductance amplifier incorporates both n-type MOS (NMOS) and p-type MOS (PMOS) devices to achieve a higher transconductance for a given bias current. However, the
additional capacitance contributed by the PMOS transistors limits the tuning range further.

An important issue in fully monolithic LC oscillators is the trade-off between the phase noise and the tuning range. For a given power dissipation, the relative phase noise decreases as the value of the tank inductance increases, but at the cost of making the capacitance of the transistors and the inductor a significant part of the tank. As a result, the variable component of the tank capacitance drops. Also, at low supply voltages, the variation obtained from a varactor diode becomes more limited.

At present, oscillators used in demanding applications such as cellular telephones still incorporate external resonators (inductors, microstrip lines, or filters) to achieve an acceptably low phase noise and an adequate tuning range.

**Power Amplifier**

An RF power amplifier is a type of electronic amplifier used to convert a low-power radio-frequency signal into a larger signal of significant power, typically for...
driving the antenna of a transmitter. It is usually optimized to have high efficiency, high output Power (P1dB) compression, good return loss on the input and output, good gain, and optimum heat dissipation.

Power amplifiers are among the most power-hungry building blocks of RF transceivers, challenging designers by supply-efficiency-linearity trade-offs. The enormous current levels and high slew rates are the principal difficulty in the design of power amplifiers and especially the package. For example, with a peak current of several amperes through the output transistor, the slew rate at 900 MHz is on the order of 10 A/ns. Thus, even parasitic resistances on the order of tens of milliohms and inductances on the order of tens of picoohmies may result in considerable loss of efficiency. For these reasons, many layout and packaging issues that are usually unimportant in other analog and RF circuits become crucial in power amplifiers.

The figure below shows a power amplifier. The circuit consists of an input matching network, several tuned gain stages, an output stage and an output matching network. The gain stages serve to both amplify the voltage swings and provide high drive capability for the output transistor.

![CMOS power amplifier](image)