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Analysis and Design of Quadrature Oscillators

by

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To the authors' families

Preface

Modern RF receivers and transmitters require quadrature oscillators with accurate quadrature and low phase-noise. Existing literature is dedicated mainly to single oscillators, and is strongly biased towards LC oscillators. This book is devoted to quadrature oscillators and presents a detailed comparative study of LC and RC oscillators, both at architectural and at circuit levels. It is shown that in cross-coupled RC oscillators both the quadrature error and phase-noise are reduced, whereas in LC oscillators the coupling decreases the quadrature error, but increases the phase-noise. Thus, quadrature RC oscillators can be a practical alternative to LC oscillators, especially when area and cost are to be minimized.

The main topics of the book are: cross-coupled LC quasi-sinusoidal oscillators, cross-coupled RC relaxation oscillators, a quadrature RC oscillator-mixer, and two-integrator oscillators. The effect of mismatches on the phase-error and the phase-noise are thoroughly investigated. The book includes many experimental results, obtained from different integrated circuit prototypes, in the GHz range.

A structured design approach is followed: a technology independent study, with ideal blocks, is performed initially, and then the circuit level design is addressed.

This book can be used in advanced courses on RF circuit design. In addition to post-graduate students and lecturers, this book will be of interest to design engineers and researchers in this area.

The book originated from the PhD work of the first author. This work was the continuation of previous research work by the authors from TUDelft and University of Alberta, and involved the collaboration of 5 persons in three different institutions. The work was done mainly at INESC-ID (a research institute associated with Technical University of Lisbon), but part of the PhD work was done at TUDelft and at the University of Alberta. This has influenced the work, by combining different views and backgrounds.

This book includes many original research results that have been presented at international conferences (ISCAS 2003, 2004, 2005, 2006, 2007 among others) and published in the IEEE Transactions on Circuits and Systems.

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Contents

Chapter 1
Introduction

Contents

1.1 Background and Motivation

The huge demand for wireless communications has led to new requirements for wireless transmitters and receivers. Compact circuits, with minimum area, are required to reduce the equipment size and cost. Thus, we need a very high degree of integration, if possible a transceiver on one chip, either without or with a reduced number of external components. In addition to area and cost, it is very important to reduce the voltage supply and the power consumption [1, 2].

Digital signal processing techniques have a deep impact on wireless applications. Digital signal processing together with digital data transmission allows the use of highly sophisticated modulation techniques, complex demodulation algorithms, error detection and correction, and data encryption, leading to a large improvement in the communication quality. Since digital signals are easier to process than analogue signals, a strong effort is being made to minimize the analogue part of the transceivers by moving as many blocks as possible to the digital domain.

The analogue front-end of a modern wireless communication system is responsible for the interface between the antenna and the digital part. The analogue front-end of a receiver is critical, the specifications of its blocks being more stringent than those of the transmitter. There are two basic receiver front-end architectures: heterodyne, with one intermediate frequency (IF), or more than one; homodyne, without intermediate frequency. So far, the heterodyne approach is dominant, but the homodyne approach, after remaining a long time in the research domain, is becoming a viable alternative [1, 2].

The main drawback of heterodyne receivers is that both the wanted signal and the disturbances in the image frequency band are downconverted to the IF. Heterodyne receivers have better performance than homodyne receivers when high quality RF

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(radio frequency) image-reject and IF channel filters can be used. However, such filters can only be implemented off chip (so far), and they are expensive. A high IF is required because, with a low-IF, the image frequency band is so close to the desired frequency that an image-reject RF filter is not feasible.

Homodyne receivers do not suffer from the image problem, because the RF signal is directly translated to the baseband (BB), without any IF. Thus, the main drawbacks of the heterodyne approach (image interference and the use of external filters) are overcome, allowing a highly integrated, low area, low power, and low cost receiver. However, homodyne receivers are very sensitive to parasitic baseband disturbances and to 1/*f* noise. Quadrature errors introduce cross-talk between the I (in-phase) and Q (quadrature) components of the received signal, which in combination with additive noise increases the bit error rate (BER).

A very interesting receiver approach, which combines the best features of the homodyne and of the heterodyne receivers, is the low IF receiver [3–7]. This is basically a heterodyne receiver using special mixing circuits that cancel the image frequency. Since image reject filters are not required, there is the possibility of using a low IF, allowing the integration of the whole system on a single chip [4]. The low-IF receiver relaxes the IF channel select filter specifications, because it works at a relatively low frequency and can be integrated on-chip, sometimes digitally. The image rejection is dependent on the quality of image-reject mixing, which depends on component matching and LO (local oscillator) quadrature accuracy. Thus, very accurate quadrature oscillators are essential for low-IF receivers.

Conventional heterodyne structures, with high IF, make the analogue to digital converter (A/D) specifications very difficult to fulfil with reasonable power consumption; therefore, the conversion to baseband has to be done in the analogue domain. In the low-IF architecture, the two down converted signals are digitized and mixed digitally to obtain the baseband as shown in Fig. 1.1.

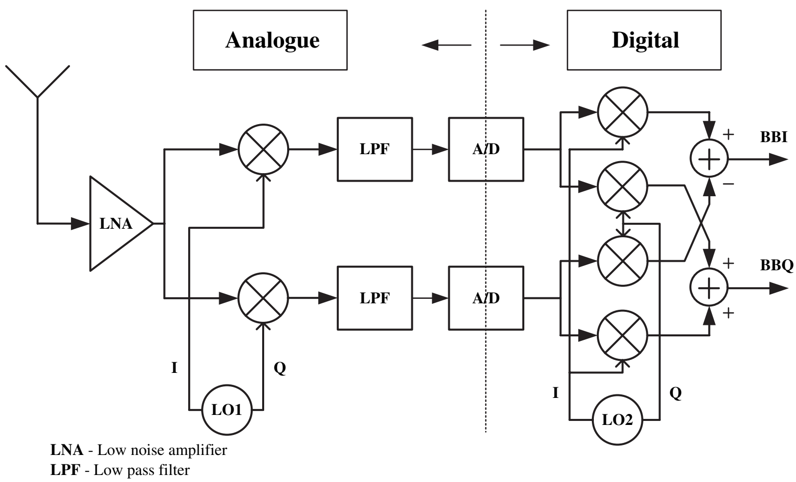

Fig. 1.1 Low-IF receiver (simplified block diagram)

The LO is a key element in the design of RF frontends. The oscillator should be fully integrated, tunable, and able to provide two quadrature output signals [8–11], I and Q. In addition to frequency and phase stability, quadrature accuracy is a very important requirement of quadrature oscillators.

The most often used circuits to obtain two signals in quadrature have open-loop structures, in which the errors are propagated directly to the output. Examples of such structures are [1]:

1. Passive circuits to produce the phase-shift (RC-CR network), in which the phase difference and gain are frequency dependent.
2. Oscillators working at double of the required frequency, followed by a divider by two; this method leads to high power consumption, and reduces the maximum achievable frequency.
3. An integrator with the in-phase signal at the input, followed by a comparator to obtain the signal in quadrature (aligned with the zero crossings of the integrator output); this has the disadvantage that the two signal paths are different.

In recent years, significant effort has been invested in the study of oscillators with accurate quadrature outputs [9–11]. Relaxation and LC oscillators, when cross-coupled (using feedback structures), are able to provide quadrature outputs. In this book these oscillators are studied in depth, in order to understand their key parameters, such as phase-noise and quadrature error.

The relaxation oscillator has been somewhat neglected with respect to the LC oscillator, as it is widely considered as a lower performance oscillator in terms of phase-noise. Although this is true for a single oscillator, it is not for cross-coupled oscillators.

In this work we consider alternatives to the LC oscillator and investigate their advantages and limitations. We study in detail the quadrature relaxation oscillators in terms of their key parameters, showing that due to the cross-coupling it is possible to reduce the oscillator phase-noise and make the effect of mismatches a second order effect, thus improving the accuracy of the quadrature relationship. We show that, although stand-alone LC oscillators have a very good phase-noise performance, this is degraded when there is cross coupling.

In addition to these two types of quadrature oscillators, we investigate a third type of oscillator: the two-integrator oscillator. While in the previous cases we had two oscillators with coupling to provide quadrature outputs, this oscillator is able to provide inherent quadrature outputs, with phase-noise comparable to that of a relaxation oscillator. The main advantage of this oscillator is its wide tuning range, which in a practical implementation (in the GHz range) can be about one decade.

Mixers are responsible for frequency translation, upconversion and downconversion, with a direct influence on the global performance of the transceiver [1,2]. They have been realized as independent circuits from the oscillators, either in heterodyne or homodyne structures. The evolution of mixer circuits has been, so far, essentially due to technological advancements in the semiconductor industry. Here, we show that it is possible to integrate the mixing function with the quadrature oscillators. This approach has the advantage of saving area and power, leading to a more accurate output quadrature than that obtained with separate quadrature oscillators and mixers. We study the influence of the mixing function on the oscillator performance, and we confirm by measurement the oscillator-mixer concept. However, the main emphasis of this book is on the oscillators: the inclusion of the mixing function still requires further study.

In this work we study in detail the three types of quadrature oscillators referred above, and we evaluate their relative advantages and disadvantages. Simulation and experimental results are provided which confirm the theoretical analysis.

1.2 Organization of the Book

This book is organized in 8 Chapters. Following this introduction, we present a survey, in Chapter 2, of RF front-ends and their main blocks: we describe the basic receiver and transmitter architectures, then we focus on basic aspects of oscillators and mixers, and, finally, we review conventional techniques to generate quadrature signals.

In Chapter 3 we present a study of the quadrature relaxation oscillator, in which we consider their key parameters: oscillation frequency, signal amplitude, quadrature relationship, and phase-noise. We use a structured approach, starting by considering the oscillator at a high level, using ideal blocks, and then we proceed to the analysis at circuit level. We present simulation results to confirm the theoretical analysis.

In Chapter 4 we analyse the quadrature relaxation oscillator-mixer. We first evaluate the circuit at a high level (structured approach), deriving equations for the oscillation frequency and quadrature error of the oscillator-mixer. We show that we can inject the modulating signal in the circuit feedback loop, and we explain where and how the RF signal should be injected, to preserve the quadrature relationship. Simulation results are provided to validate theoretical results.

In Chapter 5 the quadrature LC oscillator is studied in terms of the oscillation frequency, signal amplitude, Q, and phase-noise. We investigate the possibility of injecting a signal to perform the mixing function.

In Chapter 6 we study the two-integrator oscillator. We proceed from a high level description to the circuit implementation, and we present simulation results. We also show the possibility of performing the mixing function in this oscillator.

In Chapter 7 we present several circuit implementations to provide experimental confirmation of the theoretical results:

– a 2.4 GHz quadrature relaxation oscillator and a 1 GHz quadrature LC oscillator;
– two 5 GHz quadrature oscillators, one RC and the other LC, designed to be suitable for a comparative study;
– a 5 GHz RC oscillator-mixer (to demonstrate the study in chapter 4).

In Chapter 8 we present the conclusions and suggest future research directions.

In the appendix we describe the measurement setup for the above mentioned prototypes.

1.3 Main Contributions

The work that we present in this book has led to several papers in international conferences and journals. It is believed that the main original contributions of the work are:

(i) A study (in Chapter 3) of cross-coupled relaxation oscillators using a structured design approach: first with ideal blocks, and then at circuit level. Equations are derived for the oscillation frequency, amplitude, phase-noise, and quadrature relationship [12–15]. A prototype at 2.4 GHz was designed to confirm the main theoretical results (quadrature relationship and phase-noise).

(ii) A study of a cross-coupled relaxation oscillator-mixer at high level (in chapter 4) [12, 16–18] and investigation of the influence of the mixing function on the oscillator performance. A 5 GHz prototype was designed to validate the oscillator-mixer concept [19].

(iii) A study of cross-coupled LC oscillators concerning Q and phase-noise (in Chapter 5) [20,21]. A comparative study of phase-noise in cross-coupled oscillators, which shows that coupled relaxation oscillators can be a good alternative to coupled LC oscillators [14]. A 1 GHz prototype confirms the increase of phase-noise in LC oscillators due to coupling [21], and two circuit prototypes at 5 GHz (RC and LC) confirm that quadrature RC oscillators might be a good alternative to quadrature LC oscillators.

A minor contribution is the study of the two-integrator oscillator at high level and at circuit level (in Chapter 6), in which we show that this circuit has the advantage of a large tuning range when compared with the previous ones [22].

The work reported in this book has led to further results on quadrature oscillators, with other coupling techniques [23–25]. A pulse generator for UWB-IR based on a relaxation oscillator has been proposed recently [26]. These results, however, are outside of the scope of this book.

Chapter 2
Transceiver Architectures and RF Blocks

Contents

2.1 Introduction

In this chapter we review the basic transceiver (*trans*mitter and re*ceiver*) architectures, and some important front-end blocks, namely oscillators and mixers. We give special attention to the conventional methods to generate quadrature signals.

We start by describing the advantages and disadvantages of several receiver and transmitter architectures. Receivers are used to perform low-noise amplification, downconversion, and demodulation, while transmitters perform modulation, upconversion, and power amplification. Receiver and transmitter architectures can be divided into two types: heterodyne, which uses one or more IFs (intermediate frequencies), and homodyne, without IF. Nowadays research is more active concerning the receiver path, since requirements such as integrability, interference rejection, and

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