Fundamentals of High-Frequency CMOS Analog Integrated Circuits

With a design-centric approach, this textbook bridges the gap between fundamental analog electronic circuits textbooks and more advanced RF IC design texts. The structure and operation of the building blocks of high-frequency ICs are introduced in a systematic manner, with an emphasis on transistor-level operation, the influence of device characteristics and parasitic effects, and input–output behavior in the time and frequency domains.

Key features include:

- solved design examples to guide the reader through the decision process that accompanies each design task, with an emphasis on key trade-offs;
- coverage of the major issues that must be taken into account when combining analog and digital circuit building blocks;
- key criteria and parameters that are used to describe system-level performance;
- simple circuit models to enable a robust understanding of high-frequency design fundamentals;
- SPICE simulations that are used to check results and fine-tune the design.

This textbook is ideal for senior undergraduate and graduate courses in RF CMOS circuits, RF circuit design, and high-frequency analog circuit design. Analog integrated circuit designers and RF circuit designers in industry who need help making design choices will also find this a practical and valuable reference.

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To
Yıldız Leblebici – wife, mother, and colleague.

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Preface

In the first half of the twentieth century the radio was the main activity area of the electronics industry and, correspondingly, RF circuits occupied a considerable part in the electronic engineering curriculum and books published in this period. Properties of resonance circuits and electronic circuits using them, single-tuned amplifiers as the input stages of receivers, double-tuned circuits as IF amplifiers, RF sinusoidal oscillators and high-power class-C amplifiers have been investigated in depth. It must be kept in mind that the upper limit of the radio frequencies of those days was several tens of MHz, the inductors used in tuned circuits were air-core or ferrite-core coils with inductance values in the micro-henries to milli-henries range, having considerably high quality factors, ranging from 100 to 1000, and the tuning capacitors were practically lossless.

The knowledge developed for the vacuum-tube circuits easily adapted to the transistors with some modifications related to the differences of the input and output resistances of the devices. In the meantime, the upper limit of the frequency increased to about 100 MHz for FM radio and to hundreds of MHz for UHF-TV. The values of the inductors used in these circuits correspondingly decreased to hundreds to tens of nano-henries. But these inductors were still wound, high-Q discrete components.

In the second half of the twentieth century, the emergence of integrated circuits drastically increased the reach of electronic engineering. Digital electronics on one side and analog electronics using the potentials of the operational amplifiers on the other side forced the curricula and the textbooks to skip certain old and "already known" subjects (among them resonance circuits and tuned amplifiers), to open room to these new subjects. The development of (inductorless) active filters that replaced the conventional passive LC filters extensively used in telecommunication systems even decreased the importance of inductors.

Rapid development of CMOS technology and the steady decrease of the dimensions of the devices according to "Moore's Law" led to an increase in the complexity of ICs (from now on, the VLSI circuits) and the operating frequencies as well. In the digital realm this helped to improve the performances of digital computers and digital telecommunication systems. In the analog realm the operation frequencies of the circuits increased to the GHz region and correspondingly the inductance values decreased to below 20 nH, so that now it was possible to realize them as on-chip components. Hence the freedom from external bulky discrete inductors opened a new horizon towards small and light-weight mobile systems; the mobile telephone, GPS systems, Bluetooth, etc.

But there is a problem related to this development; the quality factors of on-chip inductors are very low, usually around 10–100, and tuning capacitors are not lossless any more. Most of the earlier theory (and design practice) that was developed with very high-Q discrete components does not easily translate to such integrated high-frequency circuits and on-chip components with less than ideal characteristics. Instead of relying on the comprehensive theory and analytical design of high-frequency analog circuits that was in place many decades earlier, most of the new-generation designers were tempted to adopt rather ad-hoc design strategies not grounded in sound theory, and to explain away the inevitable inconsistencies as “secondary effects”. To make matters even more complicated, systematic treatment of subjects such as high-frequency circuit behavior and resonance/tuned circuits has been missing from the electrical engineering curricula for several decades, and analog designers entering the field of RF/high-frequency design had to re-learn these subjects.

One of the objectives of this book is to fill this gap; to introduce the fundamental aspects of high-frequency circuit operation, to systematically discuss the behavior of key components (in particular, submicron MOSFETs and on-chip passive components), summarize the behavior of the series and parallel resonance circuits in detail and investigate the effects of the losses of on-chip inductors and capacitors that are usually not taken into account in formulas derived for high-Q resonance circuits.

Since all these circuits are being developed and used usually in the GHz range, sometimes close to the physical limits of the devices, it becomes necessary to recapitulate the behavior of MOS transistors together with their important parasitics and the frequency related secondary effects.[1] In Chapter 1 the basic current–voltage relations of MOS transistors are derived, taking into account the parabolic (not linear) shape of the inversion charge profile that leads to a different approach to understand the channel shortening effect and the gate-source capacitance of the transistor. The velocity saturation effect and the behavior of a MOS transistor under a velocity saturation regime are also investigated as an important issue for small geometry devices. Although it is not used extensively for HF applications, the sub-threshold regime is also investigated in brief.

In addition to the intrinsic behavior of MOS transistors the parasitics – that are inevitable and have severe effects on the overall behavior especially at high frequencies – have been discussed, mostly in connection with the BSIM3 parameters. The properties, limits and parasitics of the passive on-chip components, namely resistors, fixed value and variable capacitors (varactors) and inductors are also summarized in this chapter from a realistic and design-oriented point of view.

The subject of Chapter 2 is the DC properties of the basic analog MOS circuits that will be investigated in the following chapters. The interactive use of analytic

[1] This part of the book must not be considered as an alternative to the existing sound and comprehensive models such as EKV and others, but rather as an attempt to explain the behavior of MOS transistors, based on the basic laws of electrostatics and circuit theory that all electronics students already know.

expressions – that provide interpretable knowledge about the basic behavior of the circuit – and SPICE simulations – that give the designer a possibility to "experiment", to fine-tune and optimize the circuit, all secondary and parasitic effects included – are exemplified throughout the chapter. It is believed that to have the ability of using together the analytical expressions and the power of SPICE is a "must" for an analog designer.

In Chapter 3 the frequency-dependent behaviors of the basic circuits are given, not limited to the frequency characteristics of the gain but including the input and output impedances. The important properties of them, usually not dealt with in books, are investigated and their effects on the performance of wide-band circuits are underlined. The basics of the techniques used to enhance the gain; the additive approach (distributed amplifiers) and the cascading strategies to reach to the wide-band amplifiers (not only voltage amplifiers, but also current amplifiers, transadmittance amplifiers and transimpedance amplifiers) are systematically investigated.

In Chapter 4 first the resonance circuits are recapitulated with this approach and the behavioral differences of high-Q and low-Q resonance circuits are underlined. Afterwards, tuned amplifiers are systematically investigated taking into account the low-Q effects, not only for single-tuned amplifiers but also for double-tuned and staggered tuned amplifiers that are not covered in many new (and even older) books in detail. The LNA, that is one of the most important classes of tuned amplifiers, is also investigated in this chapter together with the noise behavior of MOS transistors, that is developed with a different approach.

LC sinusoidal oscillators are discussed in Chapter 5 with the negative resistance approach and the classical positive feedback approach as well, with emphasis on the effects of the low-Q components. The problems related to the frequency stability of LC oscillators are discussed and the phase noise in LC oscillators is investigated with a different approach.

The last chapter is devoted to a summary of the higher-level system view of HF analog circuits, especially in the context that virtually all such high-frequency circuits are eventually integrated with considerable digital circuitry for interface, post-processing and calibration purposes – and that such integration is increasingly done on the same silicon substrate. The traditional system-level view of high-frequency components and circuits is strongly influenced by conventional (all-analog) modulation and transmission systems modeling, which is based almost exclusively on the frequency domain. The behavior of all digital systems, on the other hand, is preferably described in the time domain. While the translation between these two domains is (in theory) quite straightforward, the designers must develop a sense of how some of their choices in the analog realm eventually influence the behavior of the digital part, and vice versa. Data converters (analog-to-digital and digital-to-analog converters) naturally play an important role in this translation between domains, and Chapter 6 attempts to summarize the key criteria and parameters that are used to describe system-level performance.

The target audience of this book includes advanced undergraduate and graduate-level students who choose analog/mixed-signal microelectronics as their area of specialization, as well as practicing design engineers. The required background that is needed to follow the material is consistent with the typical physics, math and circuits background that is acquired by the third (junior) year of a regular electrical and computer engineering (ECE) curriculum.

Solved design examples are provided to guide the reader through the decision process that accompanies each design task, emphasizing key trade-offs and eventual approximations.

A number of individuals have contributed with their time and their efforts to the creation of this textbook. In particular, both authors would like to thank Mrs Yildiz Leblebici who read the entire manuscript, carefully checked the analytical derivations throughout all chapters, and provided valuable insight as an experienced electronics teacher. The authors also acknowledge the generous support of Mr Giovanni Chiappano from austriamicrosystems A.G.[2] for offering the use of transistor parameters in numerous examples.

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[2] Device characteristics and technology parameters provided by austriamicrosystems A.G. will be labeled with the acronym "AMS" throught the text.