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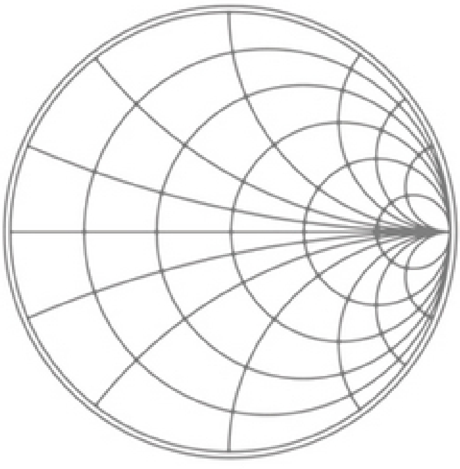
RF circuit design

second edition



Richard Chi-Hsi Li

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SECOND EDITION

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CONTENTS

PREFACE TO THE SECOND EDITION

I wrote the book titled *RF Circuit Design* in the United States, which was published by John Wiley & Sons, Inc. in 2009. It contains three parts:

1. Introduction to individual RF circuit block design. This part resembles existing books on RF circuit design. The topics concern main RF blocks such as the LNA (low-noise amplifier), Mixer, PA (power amplifier), VCO (voltage-controlled oscillator), PLL (phase lock loop), and so on. Most published RF books or articles focus largely on the description of operating principles of the circuitry. Distinctively, this part of the book emphasizes the actual engineering design procedures and schemes.

   This part could be categorized as "longitudinal."
2. Summary of skills and technologies in RF circuit design. Instead of describing circuit operating principles, the second part describes general design skills and technologies, such as impedance matching, RF grounding, layout, jeopardy in RFIC and SOC (system-on-a-chip) design, 6σ design, and so on. This part is derived from my own design experience of over 20 years, highlighting both successes and failures. Therefore, it is unique among the published books on RF circuit design and represents the special feature of this book.

   This part could be categorized as "transversal."
3. Basic parameters of an RF system and the fundamentals of RF system design. This part considers a "must" theoretical background to an RF circuit designer, who should fully understand the basic RF parameters so that he can design the RF circuitry to serve the entire system.

Till date, more than 60 lectures on the subjects of this book have been held in mainland China, Taiwan, Hong Kong, and Singapore.

I received many precious comments and valuable inputs from readers after the first edition was published. This encouraged me and promoted the desire to work on a second edition. The following are the main changes in this book from the first edition:

1. Emphasis of the skills and technologies in RF circuit design. In order to emphasize the importance of the skills and technologies in the RF circuit design, the second part in the first edition that covers skills and technologies in RF circuit design is shifted as the first part in the second edition. To an RF circuit designer, no matter whether he or she would like to be a good engineer, a qualified professor, or an authoritative academic, the foremost objective is to master the design skills and technologies in the RF circuit design.
2. It is expected that this book can be adapted as a textbook for university courses. In order to help students further familiarize themselves with the topics of this

book, exercises are included at the end of each chapter. This may be convenient to those professors who would like to select this book as a textbook in their electrical engineering courses. In other words, it is expected that this book would be not only a science–technology–engineering reference but also a candidate for a textbook.

3. Expansion of topics. In addition to the rearranging of chapters or paragraphs, some chapters have been split up and new chapters have been inserted, increasing the number of chapters from 18 in the first edition to 21 in the second edition.

Finally, I express my deep appreciation to my lovely sons, Bruno Sie Li and Bruce Xin Li, who checked and corrected my English writing for this book. Also, it should be noted that unconventional descriptions, prejudices, or mistakes may inevitably appear in this book since most of the raw material comes from my own engineering designs and theoretical derivations. Comments or corrections from readers would be highly appreciated. My email address is chihsili@yahoo.com.cn.

Fort Worth, TX, USA, 2011 RICHARD CHI HSI LI

PART 1

DESIGN TECHNOLOGIES AND SKILLS

1

DIFFERENCE BETWEEN RF AND DIGITAL CIRCUIT DESIGN

1.1 CONTROVERSY

For many years, there has been continued controversy between digital and RF circuit designers, some of which are given below:

- RF circuit designers emphasize impedance matching, whereas digital circuit designers are indifferent to it.
- RF circuit designers are concerned with frequency response, whereas digital circuit designers are interested in the waveform, or "eye's diagram." In other words, RF circuit designers prefer to work in the frequency domain, whereas digital circuit designers like to work in the time domain.
- As a consequence of the above, in a discussion of the budget for equipment, RF circuit designers like to purchase good network analyzers, whereas digital circuit designers prefer to buy the best oscilloscopes.
- RF circuit designers use the unit of dB_W, whereas digital circuit designers insist on using dB_V.
- Not only are the design methodologies different, so are their respective jargons. Digital circuit designers talk about AC bypass capacitors or DC blocking capacitors, but RF circuit designers rename those as "zero" capacitors.

It almost seems as if they were two different kinds of aliens from different planets. Even in some conferences or publications, these two kinds of "aliens" argue with

RF Circuit Design, Second Edition. Richard Chi Hsi Li.

each other. Each tries to prove that their design methodology is superior to the others'. Eventually, nobody is the winner.

Let us outline the main controversies in the following.

1.1.1 Impedance Matching

The phrase "impedance matching" comes out of RF circuit designers' mouths almost everyday. They were told by their supervisors that impedance matching is a "must" skill in circuit design. On the other hand, such terminology is never heard among digital circuit designers. Their supervisors tell them, "ignore that 'foreign language' just focus on the 'eye diagram,' or waveform."

It is not just digital circuit designers who ignore impedance matching. Even some RF circuit designers "discovered" something new in their "advanced" RFIC (RF integrated circuit) design. While it was necessary to take care of impedance matching in RF module design or in RF blocks built by discrete parts, where the incident and reflected power in the circuit really existed, they thought it unnecessary to take care of impedance matching in an RFIC circuit design because the size of an IC die is so small as to render distinguishing the incident and reflective power or voltage redundant or meaningless. In agreement with their assertions, in the IC realm the design methodology for the RF circuit should be more or less the same as that for the digital circuit. Since then, they have been designing RF circuit blocks with the same method as used for digital circuit blocks. All the individual RF blocks are simply crowded together since "impedance matching between the individual blocks is not necessary." Their design methodology for RF blocks is specially named as the "Combo" or "Jumbo" design. Theoretically, they thought that all kinds of circuitry must obey Ohm's law and follow KCL (Kirchhoff's current law) and KVL (Kirchhoff's voltage law) rules without exception. So, why is the difference of design methodology? From their viewpoint, it seems unnecessary to divide the circuit design team into an RF and a digital circuit design group accordingly.

RF circuit designers would be very happy if impedance matching was unnecessary because impedance matching is the most difficult task in RF circuit design, especially in RFIC design for the UWB (ultrawide-band) system. Unfortunately, design experience indicates that the Combo or Jumbo design philosophy is absolutely wrong. For instance, without impedance matching, a LNA (low-noise amplifier) becomes a noisy attenuator or an oscillator in an RFIC chip. Without impedance matching, a mixer would become a "real" mixer indeed, blending all desired signals and undesired interference or noise together!

The key point to stop the controversy is whether the concept of voltage or power reflection is available in RF or digital circuitry. Should the reflection of voltage or power not exist in a practical circuitry, the idea of a Combo or Jumbo design could be a correct design methodology. On the contrary, if the reflection of voltage or power exists in a practical circuitry, impedance matching would be important for power transportation or manipulation in a circuitry, and then the idea of Combo or Jumbo design would be an incorrect design methodology.

As a matter of fact, the existence of power or voltage reflection can be deduced from a rough analysis of an RF block. For example, without impedance matching, the insertion loss of an LC passive filter could be significant. However, if the Q values of the inductors or capacitors are high, the LC passive filter itself should not conceivably produce a loss of power. This significant insertion loss demonstrates that quite a lot of power is reflected from the filter or load to the source. On the other hand, power or voltage reflection is not related to the size of the block but to the impedance matching status between the source and the load. A simple example could illustrate the validity of such an assertion: light is reflected from a mirror in the same way no matter whether the light source is far from or very close to the mirror.

1.1.2 Key Parameter

There is a true story from a start-up company researching and developing a wireless communication system.

In spite of different opinions and various comments among his engineering teams, the engineering director asked both his RF and digital circuit design teams to work together for the system design of a communication system. He ruled that *voltage* must be taken as the key parameter to measure the performance of every block, including digital and RF blocks. In other words, the goal of the input and the output in every block, no matter RF or digital, must be specified with the voltage value. This engineering director hates the RF circuit designers' incessant "gossip" about power and impedance.

The engineers did try very hard to follow his instructions. There seemed to be no problem for the digital circuit blocks. However, the engineers were confused and did not know how to specify the goals for RF blocks by voltage instead of power.

By the RF engineers' understanding, all the parameters including G (power gain), NF (noise figure), IP_3 (3rd order intercept point), and IP_2 (2nd order intercept point) applied in RF circuit design were expressed by power but not voltage. In order to follow the director's instructions, they spent a lot of time to convert all the parameters from power to voltage, since power was the traditional unit and was read by most equipment. Sometimes, the conversion was meaningless or uncertain. For instance, by the unit of voltage, CNR (carrier-to-noise ratio) at the input of the demodulator was significantly dependent on the output impedance of the stage before the demodulator and the input impedance of the demodulator. Especially when the output impedance of the stage before the demodulator and the input impedance of the demodulator were different from each other, the conversion becomes impossible. Even more awkwardly, members of audience who attended the presentation meeting held by this system design team could not understand why the values appearing in the system plan were surprisingly higher or lower than those from other companies. Eventually, after they learnt of the extraordinary instructions given by the engineering director, the part of the audience equipped with calculators at hand could not but convert those values back from voltage to power!

Among this system design team, selection of a common key parameter for both RF and digital circuit designs became a hot topic. People argued with each other without result, while the director still insisted on his original instructions. After a couple of weeks, the system design still hung in the air and, finally, for unknown reasons the plan for the system design was dropped quietly. Some RF circuit designers felt upset and left the company despite the director's exhortations: "Nothing is Impossible!"

As a matter of fact, system design for a communication system must be divided into two portions: the digital portion and the RF portion. Yes, the key parameter in the digital circuit design is voltage or current. By means of voltage or current, all the intermediate parameters can be characterized. However, the key parameter in RF circuit design must be power or impedance. By means of power and impedance, all the intermediate parameters in a RF circuit block can be characterized. Impedance matching ensures the best performance of power transportation or manipulation in RF circuit blocks; therefore, impedance can be taken as the key parameter in RF circuit design.

Why? The answer can be found in the following sections.

1.1.3 Circuit Testing and Main Test Equipment

In addition to the arguments about impedance matching and the key parameters, the difference between digital and RF circuit design can also be found in circuit testing and test equipment.

In a digital test laboratory, the test objective is always voltage, and occasionally current. There are many pieces of test equipment available in a digital test laboratory; however, the main test equipment is the oscilloscope. The oscilloscope can sense the voltage at any node in the circuitry and display its eye diagram or a waveform on screen, which characterizes the performance of a digital circuit intuitionally. In general, digital circuit designers prefer to analyze the circuitry in the time domain because the speed of response is important to the performance of a digital circuit block.

In an RF test laboratory, the test objective is always power. Most RF test equipment, such as the spectrum analyzer, noise meter, signal generator, and so on, measure the parameters of an RF circuit block in terms of power but not voltage. The main test equipment is the network analyzer. The performance of an RF circuit block can be characterized mainly by its frequency response on network analyzer screen, which is expressed by power gain or loss, in decibels. The RF circuit designer prefers to analyze the circuitry in the frequency domain because coverage of bandwidth is important to the performance of an RF block.

In the test laboratory, testing a digital circuit block is somewhat easier than testing an RF circuit block. In testing for a digital circuit block, the probe of an oscilloscope is usually a sensor with high impedance. It does not disturb the circuit performance when it touches a node in the circuitry.

On the other hand, while using a network analyzer, the circuit designers may worry about the difference of circuit performance before and after the tested equipment is connected to the desired test node, because the input and output impedance of the equipment is low, usually 50 Ω. In most cases, it certainly will disturb the circuit performance.

Instead of voltage testing, the RF circuit designer is concerned with power testing. All power testing must be conducted under a good impedance matching condition so the test equipment must be well calibrated. Unlike the testing for a digital circuit block by an oscilloscope, a buffer connected between the desired test node and the input of the network analyzer is not allowed because all the power tests for the RF block must be conducted under the condition of impedance matching.

So far, the different methodology between RF and digital circuit design has been introduced only in terms of the three main aspects above. More differences exist but will not be listed. We are going to focus on the explanation of where these differences come from.

1.2 DIFFERENCE OF RF AND DIGITAL BLOCK IN A COMMUNICATION SYSTEM

1.2.1 Impedance

The input and output impedance of an RF circuitry are usually pretty low. In most cases, they are typically 50 Ω. On the contrary, the input and output impedances in a digital circuitry are usually quite high. For example, the input and output impedances of an Op-Amp (operating amplifier) are mostly higher than 10 kΩ.

The lower impedance in an RF circuitry is beneficial to deliver power to a block or a part. It is well known that the power of a signal delivered to a block or a part with impedance Z can be expressed by

$$P = vi = \frac{v^2}{Z}, \tag{1.1}$$

where

$P =$ the power delivered to a block or a part,
$v =$ the AC or RF voltage across the block or the part,
$i =$ the AC or RF current flowing through the block or part, and
$Z =$ the impedance of the block or the part.

For a given value of power, v^2 is proportional to Z. This implies that, in order to deliver a given power to a block or a part, a higher voltage must be provided if its impedance is high. On the contrary, a lower voltage across the block is enough to deliver the same given power to a block or a part if its impedance is low. From the viewpoint of either cost or engineering design of the circuit, the application of a lower voltage is much better than that of a higher voltage. It is one of the reasons why the input and output impedance in the RF blocks are intentionally assigned to be low because only a lower voltage is needed in order to deliver the same given power to a block or part with low impedance.

However, it is just the opposite for a digital signal. The higher impedance in digital circuitry is beneficial to the voltage swing in a digital block or part. For a given current, a higher impedance can have a higher voltage swing across a block or a part, and then the signal can ON/OFF the device more effectively, because

$$v = iZ. \tag{1.2}$$

The question is: why is RF circuitry focused on the power while digital circuitry is concerned about voltage?

1.2.2 Current Drain

In RF circuit blocks, the current drains are usually in the order of milliamperes while in digital circuit blocks they are usually in the order of microamperes. That is, the difference of the current drain's magnitude between RF and digital circuit blocks is approximately 1000 times.

In RF circuit blocks, it is desirable to increase the power of the RF signal as much as possible. This implies that higher current drains are preferred in RF circuit blocks because they are beneficial to deliver power to the block or the part for a given voltage.

In digital circuit blocks, it is desirable to reduce the power of the digital signal as much as possible. This implies that lower current drains are preferred in digital circuit blocks as long as the voltage swing is high enough.

Again, the question is: why is RF circuitry focused on power while digital circuitry is concerned with voltage? The answer can be found in the following section.

1.2.3 Location

In a communication system, the demodulator is a remarkable demarcation in the receiver. As shown in Figure1.1, before the demodulator, the blocks operate in the range of radio frequency so that they are called *RF blocks*. They are sometimes called the *RF front end* in the receiver, where the RF circuit design is conducted. After demodulation, the blocks operate in the range of intermediate frequency or in the low digital data rate and are categorized as baseband blocks, or the digital/analog section. They are sometimes called the *back end* in the receiver, where digital/analog circuit design is conducted. The demodulator is a critical block in which both digital and RF design technology are needed.

The order of blocks in the transmitter is just opposite. Before the modulator, the blocks operate in the range of intermediate frequency or in the low digital data rate and are categorized as baseband blocks, or the digital/analog section. They are sometimes called the *front end* in the transmitter, where digital/analog circuit design is conducted. After the modulator, the blocks operate in the range of radio frequency so that they are called *RF blocks* and sometimes the *RF back end* in the transmitter, where RF circuit design is conducted. The modulator is also a critical block, in which both digital and RF design technology are needed.

A common feature can be seen from Figure 1.1. In either the receiver or the transmitter, the circuit portion close to the antenna side contains RF blocks and the portion farther from antenna side contains digital/analog circuit blocks.

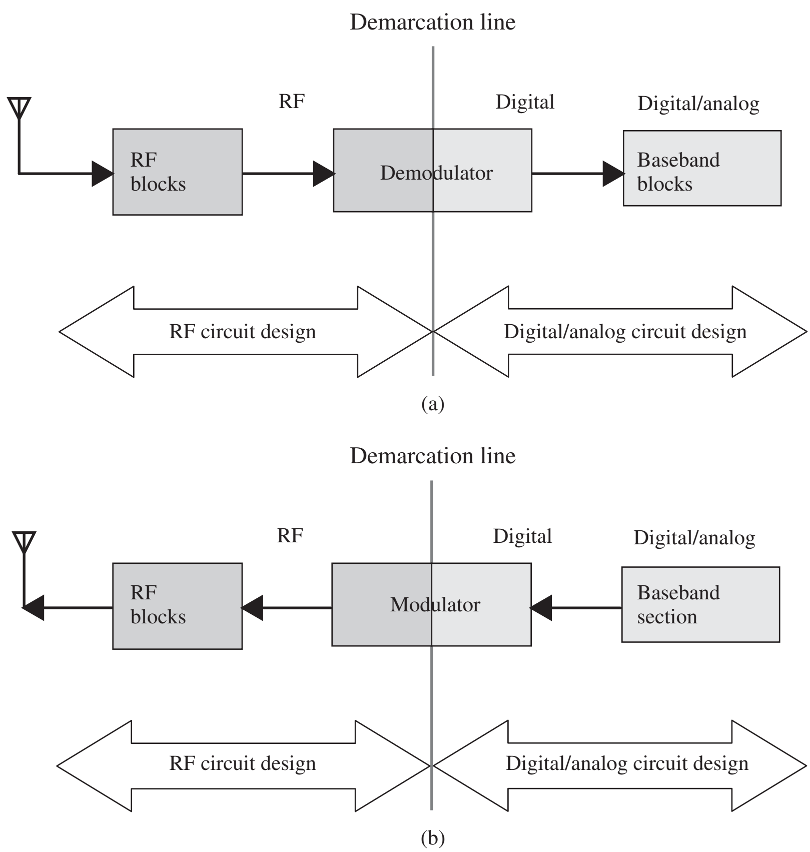

Figure 1.1. Demarcation line in a communication system. (a) Receiver. (b) Transmitter.