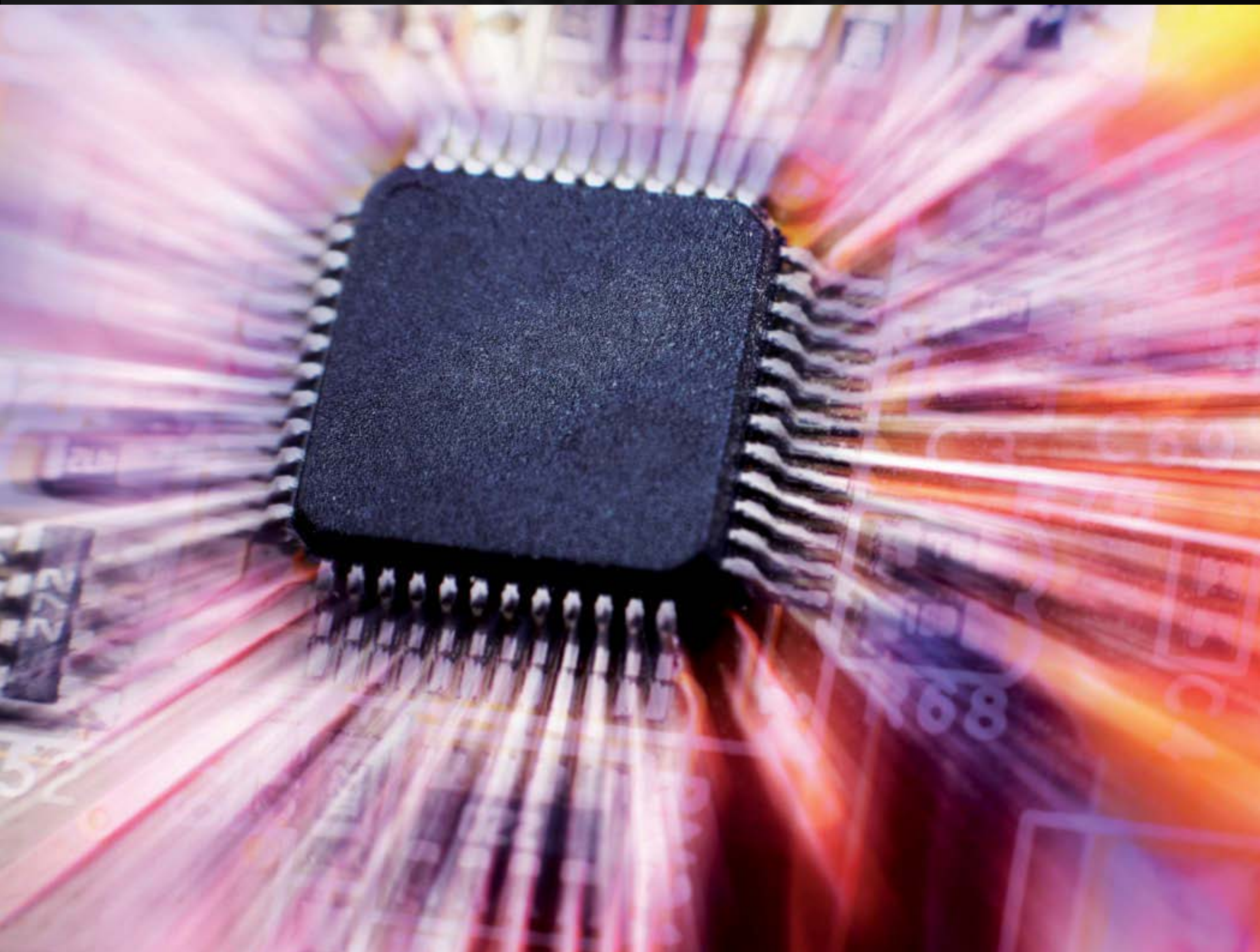
SECOND EDITION

MICROELECTRONICS

Behzad Razavi



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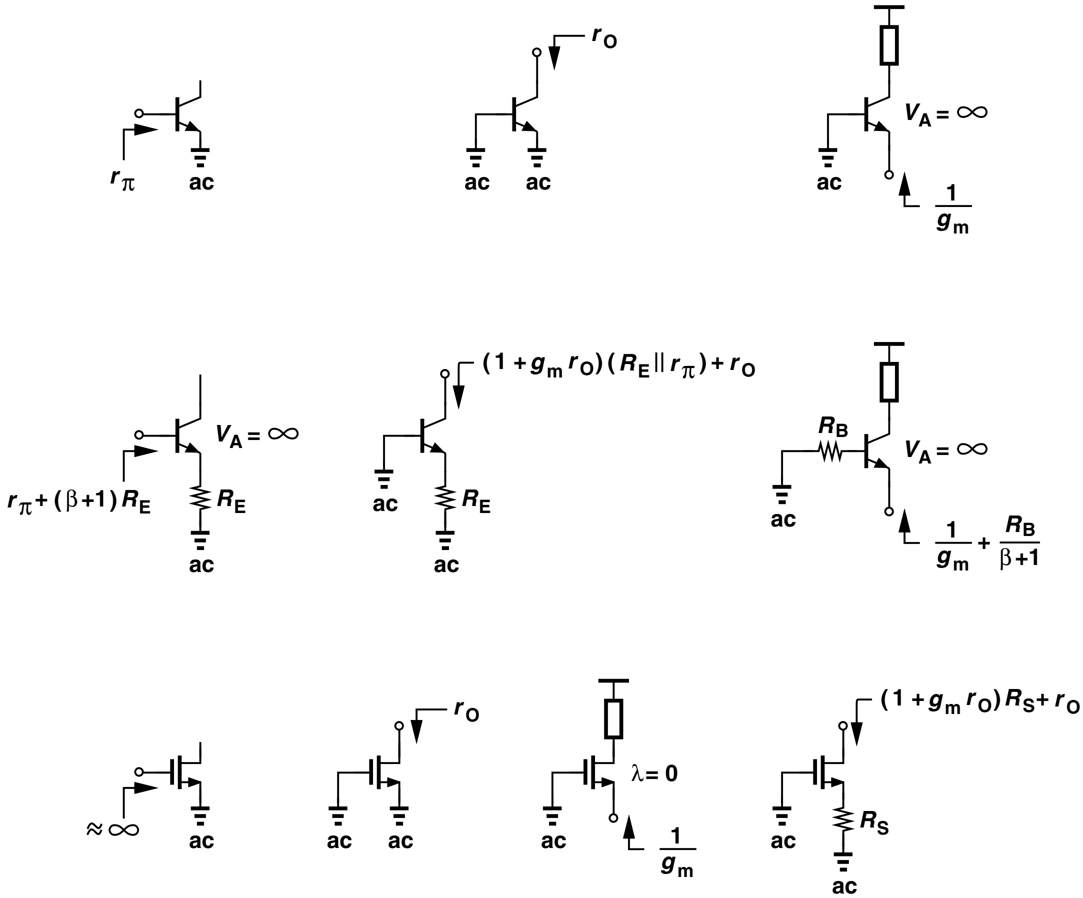

Microelectronics

Second Edition

Behzad Razavi
University of California, Los Angeles

International Student Version

WILEY

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To Angelina and Jahan,
for their love and patience

About the Author

Behzad Razavi received the BSEE degree from Sharif University of Technology in 1985 and the MSEE and PhDEE degrees from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since 1996, he has been Associate Professor and subsequently Professor of electrical engineering at University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi was an Adjunct Professor at Princeton University from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committees of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and VLSI Circuits Symposium from 1998 to 2002. He has also served as Guest Editor and Associate Editor of the IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems, and International Journal of High Speed Electronics.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC, the best paper award at the 1994 European Solid-State Circuits Conference, the best panel award at the 1995 and 1997 ISSCC, the TRW Innovative Teaching Award in 1997, the best paper award at the IEEE Custom Integrated Circuits Conference in 1998, and the McGraw-Hill First Edition of the Year Award in 2001. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He received the Lockheed Martin Excellence in Teaching Award in 2006, the UCLA Faculty Senate Teaching Award in 2007, and the CICC Best Invited Paper Award in 2009 and 2012. He was the co-recipient of the 2012 VLSI Circuits Symposium Best Student Paper Award. He was also recognized as one of the top 10 authors in the 50-year history of ISSCC. Professor Razavi received the IEEE Donald Pederson Award in Solid-State Circuits in 2011.

Professor Razavi is a Fellow of IEEE, has served as an IEEE Distinguished Lecturer, and is the author of *Principles of Data Conversion System Design, RF Microelectronics* (translated to Chinese, Japanese, and Korean), *Design of Analog CMOS Integrated Circuits* (translated to Chinese, Japanese, and Korean), *Design of Integrated Circuits for Optical Communications*, and *Fundamentals of Microelectronics* (translated to Korean and Portuguese). He is also the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* and *Phase-Locking in High-Performance Systems*.

Preface

The first edition of this book was published in 2008 and has been adopted by numerous universities around the globe for undergraduate microelectronics education. Following is a detailed description of each chapter with my teaching and learning recommendations.

Coverage of Chapters The material in each chapter can be decomposed into three categories: (1) essential concepts that the instructor should cover in the lecture, (2) essential skills that the students must develop but cannot be covered in the lecture due to the limited time, and (3) topics that prove useful but may be skipped according to the instructor's preference.[1] Summarized below are overviews of the chapters showing which topics should be covered in the classroom.

Chapter 1: Introduction to Microelectronics The objective of this chapter is to provide the "big picture" and make the students comfortable with analog and digital signals. I spend about 30 to 45 minutes on Sections 1.1 and 1.2, leaving the remainder of the chapter (Basic Concepts) for the teaching assistants to cover in a special evening session in the first week.

Chapter 2: Basic Semiconductor Physics Providing the basics of semiconductor device physics, this chapter deliberately proceeds at a slow pace, examining concepts from different angles and allowing the students to digest the material as they read on. A terse language would shorten the chapter but require that the students reread the material multiple times in their attempt to decipher the prose.

It is important to note, however, that the instructor's pace in the classroom need not be as slow as that of the chapter. The students are expected to read the details and the examples on their own so as to strengthen their grasp of the material. The principal point in this chapter is that we must study the physics of devices so as to construct circuit models for them. In a quarter system, I cover the following concepts in the lecture: electrons and holes; doping; drift and diffusion; *pn* junction in equilibrium and under forward and reverse bias.

Chapter 3: Diode Models and Circuits This chapter serves four purposes: (1) make the students comfortable with the *pn* junction as a nonlinear device; (2) introduce the concept of linearizing a nonlinear model to simplify the analysis; (3) cover basic circuits with which any electrical engineer must be familiar, e.g., rectifiers and limiters; and (4) develop the skills necessary to analyze heavily-nonlinear circuits, e.g., where it is difficult to predict which diode turns on at what input voltage. Of these, the first three are essential and should be covered in the lecture, whereas the last depends on the instructor's preference. (I cover it in my lectures.) In the interest of time, I skip a number of sections in a quarter system, e.g., voltage doublers and level shifters.

Chapter 4: Physics of Bipolar Transistors Beginning with the use of a voltage-controlled current source in an amplifier, this chapter introduces the bipolar transistor

[1]Such topics are identified in the book by a footnote.

as an extension of *pn* junctions and derives its small-signal model. As with Chapter 2, the pace is relatively slow, but the lectures need not be. I cover structure and operation of the bipolar transistor, a very simplified derivation of the exponential characteristic, and transistor models, mentioning only briefly that saturation is undesirable. Since the T-model of limited use in analysis and carries little intuition (especially for MOS devices), I have excluded it in this book.

Chapter 5: Bipolar Amplifiers This is the longest chapter in the book, building the foundation necessary for all subsequent work in electronics. Following a bottom-up approach, this chapter establishes critical concepts such as input and output impedances, biasing, and small-signal analysis.

While writing the book, I contemplated decomposing Chapter 5 into two chapters, one on the above concepts and another on bipolar amplifier topologies, so that the latter could be skipped by instructors who prefer to continue with MOS circuits instead. However, teaching the general concepts does require the use of transistors, making such a decomposition difficult.

Chapter 5 proceeds slowly, reinforcing, step-by-step, the concept of synthesis and exploring circuit topologies with the aid of "What if?" examples. As with Chapters 2 and 4, the instructor can move at a faster pace and leave much of the text for the students to read on their own. In a quarter system, I cover all of the chapter, frequently emphasizing the concepts illustrated in Figure 5.7 (the impedance seen looking into the base, emitter, or collector). With about two (perhaps two and half) weeks allotted to this chapter, the lectures must be precisely designed to ensure the main concepts are imparted in the classroom.

Chapter 6: Physics of MOS Devices This chapter parallels Chapter 4, introducing the MOSFET as a voltage-controlled current source and deriving its characteristics. Given the limited time that we generally face in covering topics, I have included only a brief discussion of the body effect and velocity saturation and neglected these phenomena for the remainder of the book. I cover all of this chapter in our first course.

Chapter 7: CMOS Amplifiers Drawing extensively upon the foundation established in Chapter 5, this chapter deals with MOS amplifiers but at a faster pace. I cover all of this chapter in our first course.

Chapter 8: Operational Amplifier as a Black Box Dealing with op-amp-based circuits, this chapter is written such that it can be taught in almost any order with respect to other chapters. My own preference is to cover this chapter *after* amplifier topologies have been studied, so that the students have some bare understanding of the internal circuitry of op amps and its gain limitations. Teaching this chapter near the end of the first course also places op amps closer to differential amplifiers (Chapter 10), thus allowing the students to appreciate the relevance of each. I cover all of this chapter in our first course.

Chapter 9: Cascodes and Current Mirrors This chapter serves as an important step toward integrated circuit design. The study of cascodes and current mirrors here also provides the necessary background for constructing differential pairs with active loads or cascodes in Chapter 10. From this chapter on, bipolar and MOS circuits are covered together and various similarities and contrasts between them are pointed out. In our second microelectronics course, I cover all of the topics in this chapter in approximately two weeks.

Chapter 10: Differential Amplifiers This chapter deals with large-signal and small-signal behavior of differential amplifiers. The students may wonder why we did not study the large-signal behavior of various amplifiers in Chapters 5 and 7; so I explain that the differential pair is a versatile circuit and is utilized in both regimes. I cover all of this chapter in our second course.

Chapter 11: Frequency Response Beginning with a review of basic concepts such as Bode's rules, this chapter introduces the high-frequency model of transistors and analyzes the frequency response of basic amplifiers. I cover all of this chapter in our second course.

Chapter 12: Feedback and Stability Most instructors agree the students find feedback to be the most difficult topic in undergraduate microelectronics. For this reason, I have made great effort to create a step-by-step procedure for analyzing feedback circuits, especially where input and output loading effects must be taken into account. As with Chapters 2 and 5, this chapter proceeds at a deliberately slow pace, allowing the students to become comfortable with each concept and appreciate the points taught by each example. I cover all of this chapter in our second course.

Chapter 13: Oscillators This new chapter deals with both discrete and integrated oscillators. These circuits are both important in real-life applications and helpful in enhancing the feedback concepts taught previously. This chapter can be comfortably covered in a semester system.

Chapter 14: Output Stages and Power Amplifiers This chapter studies circuits that deliver higher power levels than those considered in previous chapters. Topologies such as push-pull stages and their limitations are analyzed. This chapter can be covered in a semester system.

Chapter 15: Analog Filters This chapter provides a basic understanding of passive and active filters, preparing the student for more advanced texts on the subject. This chapter can also be comfortably covered in a semester system.

Chapter 16: Digital CMOS Circuits This chapter is written for microelectronics courses that include an introduction to digital circuits as a preparation for subsequent courses on the subject. Given the time constraints in quarter and semester systems, I have excluded TTL and ECL circuits here.

Chapter 17: CMOS Amplifiers This chapter is written for courses that cover CMOS circuits before bipolar circuits. As explained earlier, this chapter follows MOS device physics and, in essence, is similar to Chapter 5 but deals with MOS counterparts.

Problem Sets In addition to numerous examples, each chapter offers a relatively large problem set at the end. For each concept covered in the chapter, I begin with simple, confidence-building problems and gradually raise the level of difficulty. Except for the device physics chapters, all chapters also provide a set of design problems that encourage students to work "in reverse" and select the bias and/or component values to satisfy certain requirements.

SPICE Some basic circuit theory courses may provide exposure to SPICE, but it is in the first microelectronics course that the students can appreciate the importance of simulation tools. Appendix A of this book introduces SPICE and teaches circuit simulation with the aid of numerous examples. The objective is to master only a *subset* of SPICE commands that allow simulation of most circuits at this level. Due to the limited lecture time, I ask the teaching assistants to cover SPICE in a special evening session around the middle of the quarter—just before I begin to assign SPICE problems.

Most chapters contain SPICE problems, but I prefer to introduce SPICE only in the second half of the first course (toward the end of Chapter 5). This is for two reasons: (1) the students must first develop their basic understanding and analytical skills, i.e., the homeworks must exercise the fundamental concepts; and (2) the students appreciate the utility of SPICE much better if the circuit contains a relatively large number of devices (e.g., 5-10).

Homeworks and Exams In a quarter system, I assign four homeworks before the midterm and four after. Mostly based on the problem sets in the book, the homeworks contain moderate to difficult problems, thereby requiring that the students first go over the easier problems in the book on their own.

The exam questions are typically "twisted" versions of the problems in the book. To encourage the students to solve *all* of the problems at the end of each chapter, I tell them that one of the problems in the book is given in the exam verbatim. The exams are open-book, but I suggest to the students to summarize the important equations on one sheet of paper.

Behzad Razavi

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My wife, Angelina, typed the entire book and kept her humor as this project dragged on. My deepest thanks go to her.

Behzad Razavi

Contents

Chapter 1

Introduction to Microelectronics

Over the past five decades, microelectronics has revolutionized our lives. While beyond the realm of possibility a few decades ago, cellphones, digital cameras, laptop computers, and many other electronic products have now become an integral part of our daily affairs.

Learning microelectronics *can* be fun. As we learn how each device operates, how devices comprise circuits that perform interesting and useful functions, and how circuits form sophisticated systems, we begin to see the beauty of microelectronics and appreciate the reasons for its explosive growth.

This chapter gives an overview of microelectronics so as to provide a context for the material presented in this book. We introduce examples of microelectronic systems and identify important circuit "functions" that they employ. We also provide a review of basic circuit theory to refresh the reader's memory.

1.1 ELECTRONICS VERSUS MICROELECTRONICS

The general area of electronics began about a century ago and proved instrumental in the radio and radar communications used during the two world wars. Early systems incorporated "vacuum tubes," amplifying devices that operated with the flow of electrons between plates in a vacuum chamber. However, the finite lifetime and the large size of vacuum tubes motivated researchers to seek an electronic device with better properties.

The first transistor was invented in the 1940s and rapidly displaced vacuum tubes. It exhibited a very long (in principle, infinite) lifetime and occupied a much smaller volume (e.g., less than 1 cm^3 in packaged form) than vacuum tubes did.

But it was not until 1960s that the field of microelectronics, i.e., the science of integrating many transistors on one chip, began. Early "integrated circuits" (ICs) contained only a handful of devices, but advances in the technology soon made it possible to dramatically increase the complexity of "microchips."

Example 1.1

Today's microprocessors contain about 100 million transistors in a chip area of approximately 3 cm $\times$ 3 cm. (The chip is a few hundred microns thick.) Suppose integrated circuits were not invented and we attempted to build a processor using 100 million "discrete" transistors. If each device occupies a volume of 3 mm $\times$ 3 mm $\times$ 3 mm, determine the minimum volume for the processor. What other issues would arise in such an implementation?

Solution The minimum volume is given by 27 $mm^3 \times 10^8$, i.e., a cube 1.4 m on each side! Of course, the wires connecting the transistors would increase the volume substantially.

In addition to occupying a large volume, this discrete processor would be extremely *slow*; the signals would need to travel on wires as long as 1.4 m! Furthermore, if each discrete transistor costs 1 cent and weighs 1 g, each processor unit would be priced at one million dollars and weigh 100 tons!

Exercise How much power would such a system consume if each transistor dissipates 10 μW?

This book deals mostly with microelectronics while providing sufficient foundation for general (perhaps discrete) electronic systems as well.

1.2 EXAMPLES OF ELECTRONIC SYSTEMS

At this point, we introduce two examples of microelectronic systems and identify some of the important building blocks that we should study in basic electronics.

1.2.1 Cellular Telephone

Cellular telephones were developed in the 1980s and rapidly became popular in the 1990s. Today's cellphones contain a great deal of sophisticated analog and digital electronics that lie well beyond the scope of this book. But our objective here is to see how the concepts described in this book prove relevant to the operation of a cellphone.

Suppose you are speaking with a friend on your cellphone. Your voice is converted to an electric signal by a microphone and, after some processing, transmitted by the antenna. The signal produced by your antenna is picked up by your friend's receiver and, after some processing, applied to the speaker [Fig. 1.1(a)]. What goes on in these black boxes? Why are they needed?

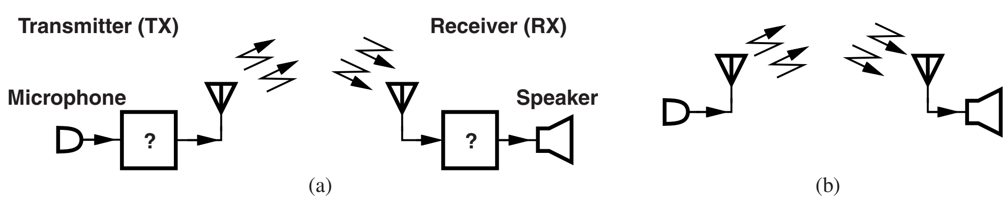

Figure 1.1 (a) Simplified view of a cellphone, (b) further simplification of transmit and receive paths.

Let us attempt to omit the black boxes and construct the simple system shown in Fig. 1.1(b). How well does this system work? We make two observations. First, our voice contains frequencies from 20 Hz to 20 kHz (called the "voice band"). Second, for an antenna to operate efficiently, i.e., to convert most of the electrical signal to electromagnetic radiation, its dimension must be a significant fraction (e.g., 25%) of the wavelength. Unfortunately, a frequency range of 20 Hz to 20 kHz translates to a wavelength[1] of 1.5×10^7 m to 1.5×10^4 m, requiring gigantic antennas for each cellphone. Conversely, to obtain a reasonable antenna length, e.g., 5 cm, the wavelength must be around 20 cm and the frequency around 1.5 GHz.

How do we "convert" the voice band to a gigahertz center frequency? One possible approach is to multiply the voice signal, $x(t)$, by a sinusoid, $A\cos(2\pi f_c t)$ [Fig. 1.2(a)]. Since multiplication in the time domain corresponds to convolution in the frequency domain, and since the spectrum of the sinusoid consists of two impulses at $\pm f_c$, the voice spectrum is simply shifted (translated) to $\pm f_c$ [Fig. 1.2(b)]. Thus, if $f_c = 1$ GHz, the output occupies a bandwidth of 40 kHz centered at 1 GHz. This operation is an example of "amplitude modulation."[2]

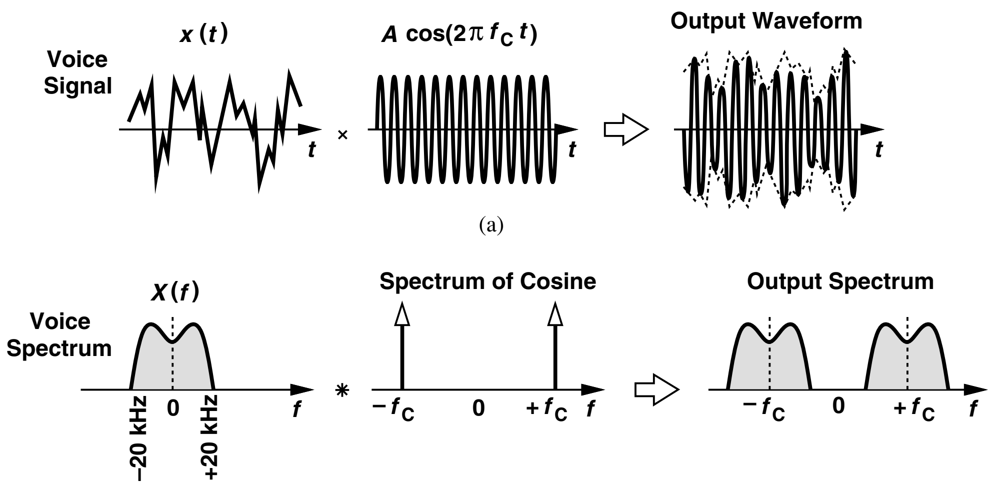

Figure 1.2 (a) Multiplication of a voice signal by a sinusoid, (b) equivalent operation in the frequency domain.

We therefore postulate that the black box in the transmitter of Fig. 1.1(a) contains a multiplier,[3] as depicted in Fig. 1.3(a). But two other issues arise. First, the cellphone must deliver a relatively large voltage swing (e.g., 20 V_{pp}) to the antenna so that the radiated power can reach across distances of several kilometers, thereby requiring a "power amplifier" between the multiplier and the antenna. Second, the sinusoid, $A\cos 2\pi f_c t$, must be produced by an "oscillator." We thus arrive at the transmitter architecture shown in Fig. 1.3(b).

[1]Recall that the wavelength is equal to the (light) velocity divided by the frequency.

[2]Cellphones in fact use other types of modulation to translate the voice band to higher frequencies.

[3]Also called a "mixer" in high-frequency electronics.

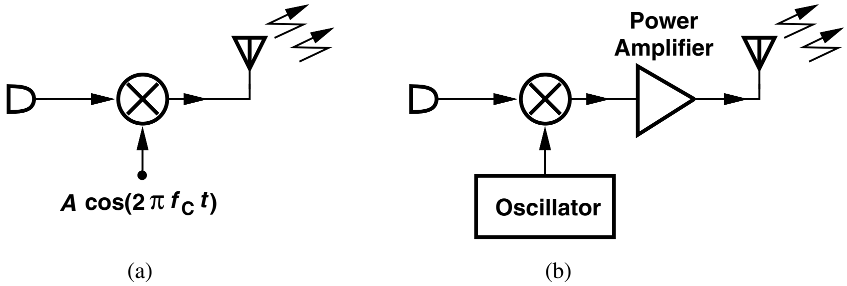

Figure 1.3 (a) Simple transmitter, (b) more complete transmitter.

Let us now turn our attention to the receive path of the cellphone, beginning with the simple realization illustrated in Fig. 1.1(b). Unfortunately, this topology fails to operate with the principle of modulation: if the signal received by the antenna resides around a gigahertz center frequency, the audio speaker cannot produce meaningful information. In other words, a means of translating the spectrum back to zero center frequency is necessary. For example, as depicted in Fig. 1.4(a), multiplication by a sinusoid, $A\cos(2\pi f_c t)$, translates the spectrum to left and right by f_c, restoring the original voice band. The newly-generated components at $\pm 2f_c$ can be removed by a low-pass filter. We thus arrive at the receiver topology shown in Fig. 1.4(b).

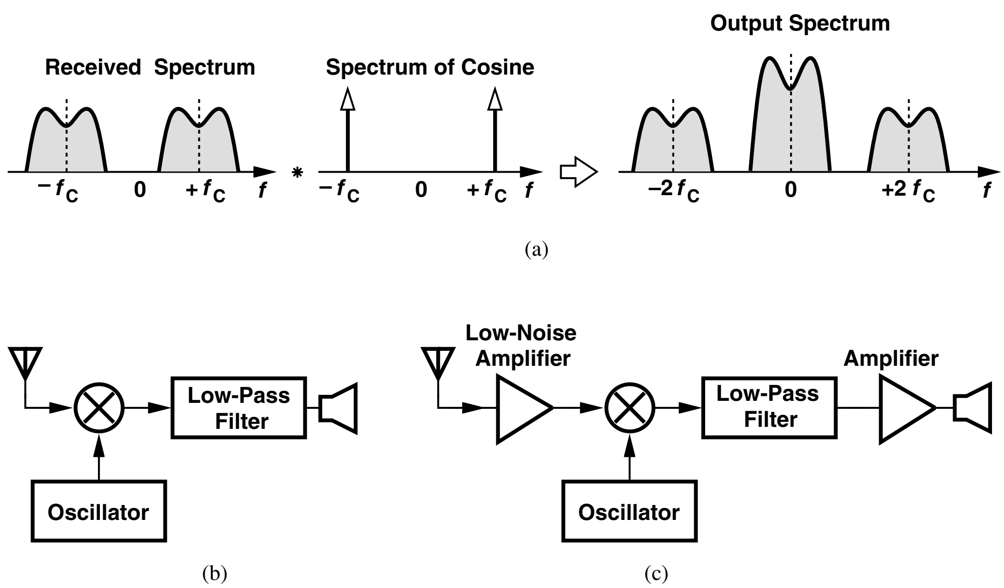

Figure 1.4 (a) Translation of modulated signal to zero center frequency, (b) simple receiver, (b) more complete receiver.

Our receiver design is still incomplete. The signal received by the antenna can be as low as a few tens of microvolts whereas the speaker may require swings of several tens or hundreds of millivolts. That is, the receiver must provide a great deal of amplification ("gain") between the antenna and the speaker. Furthermore, since multipliers typically suffer from a high "noise" and hence corrupt the received signal, a "low-noise amplifier" must precede the multiplier. The overall architecture is depicted in Fig. 1.4(c).

Today's cellphones are much more sophisticated than the topologies developed above. For example, the voice signal in the transmitter and the receiver is applied to a digital signal processor (DSP) to improve the quality and efficiency of the communication. Nonetheless, our study reveals some of the *fundamental* building blocks of cellphones, e.g., amplifiers, oscillators, and filters, with the last two also utilizing amplification. We therefore devote a great deal of effort to the analysis and design of amplifiers.

Having seen the necessity of amplifiers, oscillators, and multipliers in both transmit and receive paths of a cellphone, the reader may wonder if "this is old stuff" and rather trivial compared to the state of the art. Interestingly, these building blocks still remain among the most challenging circuits in communication systems. This is because the design entails critical *trade-offs* between speed (gigahertz center frequencies), noise, power dissipation (i.e., battery lifetime), weight, cost (i.e., price of a cellphone), and many other parameters. In the competitive world of cellphone manufacturing, a given design is never "good enough" and the engineers are forced to further push the above trade-offs in each new generation of the product.

1.2.2 Digital Camera

Another consumer product that, by virtue of "going electronic," has dramatically changed our habits and routines is the digital camera. With traditional cameras, we received no immediate feedback on the quality of the picture that was taken, we were very careful in selecting and shooting scenes to avoid wasting frames, we needed to carry bulky rolls of film, and we would obtain the final result only in printed form. With digital cameras, on the other hand, we have resolved these issues and enjoy many other features that only electronic processing can provide, e.g., transmission of pictures through cellphones or ability to retouch or alter pictures by computers. In this section, we study the operation of the digital camera.

The "front end" of the camera must convert light to electricity, a task performed by an array (matrix) of "pixels."[4] Each pixel consists of an electronic device (a "photodiode") that produces a current proportional to the intensity of the light that it receives. As illustrated in Fig. 1.5(a), this current flows through a capacitance, C_L, for a certain period of time, thereby developing a proportional voltage across it. Each pixel thus provides a voltage proportional to the "local" light density.

Now consider a camera with, say, 6.25 million pixels arranged in a 2500×2500 array [Fig. 1.5(b)]. How is the output voltage of each pixel sensed and processed? If each pixel contains its own electronic circuitry, the overall array occupies a very large area, raising the cost and the power dissipation considerably. We must therefore "time-share" the signal processing circuits among pixels. To this end, we follow the circuit of Fig. 1.5(a) with a simple, compact amplifier and a switch (within the pixel) [Fig. 1.5(c)]. Now, we connect a wire to the outputs of all 2500 pixels in a "column," turn on only one switch at a time, and apply the corresponding voltage to the "signal processing" block outside the column.

[4]The term "pixel" is an abbreviation of "picture cell."