Design of Integrated Circuits for Optical Communications

Behzad Razavi

Second Edition

WILEY

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To Angelina

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Preface to First Edition

The increasing demand for high-speed transport of data has revitalized optical communications, leading to extensive work on high-speed device and circuit design. This book has been written to address the need for a tutorial text dealing with the analysis and design of integrated circuits (ICs) for optical communication systems and will prove useful to both graduate students and practicing engineers. The book assumes a solid understanding of analog design, e.g., at the level of *Design of Analog CMOS Integrated Circuits* by B. Razavi or *Analysis and Design of Analog Integrated Circuits* by P. Gray, P. Hurst, S. Lewis, and R. Meyer.

The book comprises ten chapters. Chapter 1 provides an introduction to optical communications, setting the stage for subsequent developments. Chapter 2 describes basic concepts, building the foundation for analysis and design of circuits. Chapter 3 deals with optical devices and systems, bridging the gap between optics and electronics.

Chapter 4 addresses the design of transimpedance amplifiers, focusing on low-noise broadband topologies and their trade-offs. Chapter 5 extends these concepts to limiting amplifiers and output buffers, introducing methods of achieving a high gain with a broad bandwidth.

Chapter 6 presents oscillator fundamentals, and Chapter 7 focuses on LC oscillators. Chapter 8 describes the design of phase-locked loops, and Chapter 9 applies the idea of phase locking to clock and data recovery circuits. Chapter 10 deals with high-speed transmitter circuits such as multiplexers and laser drivers.

The book can be adopted for a graduate course on high-speed IC design. In a quarter system, parts of Chapters 3, 4, and 10 may be skipped. In a semester system, all chapters can be covered.

A website for the book provides additional resources for the reader, including an image set and web links. Visit **www.mhhe.com/razavi** for more information.

I would like to express my gratitude to the reviewers who provided invaluable feedback on all aspects of the book. Specifically, I am thankful to Lawrence Der (Transpectrum), Larry DeVito (Analog Devices), Val Garuts (TDK Semiconductor), Michael Green (University of California, Irvine), Yuriy Greshishchev (Nortel Networks), Qiuting Huang (Swiss Federal Institute of Technology), Jaime Kardontchik (TDK Semiconductor), Tai-Cheng Lee (National Taiwan University), Howard Luong (Hong Kong University of Science and Technology), Bradley Minch (Cornell University), Hakki Ozuc (TDK Semiconductor), Ken Pedrotti (University of California, Santa Cruz), Gabor Temes (Oregon State University), and Barry Thompson (TDK Semoconductor). I also wish to thank Michelle Flomenthoft, Betsy Jones, and Gloria Schiesl of McGraw-Hill for their kind support.

My wife, Angelina, encouraged me to start writing this book soon after we were married. She typed the entire text and endured my late work hours—always with a smile. I am very grateful to her.

Behzad Razavi
July 2002

Preface

The field of optical communications has experienced some change since the first edition of this book was published. While the fundemantals remain the same, the field has tried to find a place in mass markets and, specifically, spawned "passive optical networks." In addition, many new circuit techniques have been introduced for broadband applications, including optical systems.

This second edition reflects the new developments in the field. Recently reported circuit techniques for transimpedance amplifiers, broadband amplifiers, laser drivers, and clock and data recovery circuits have been described. Moreover, a new chapter dedicated to "burst-mode" circuits, i.e., building blocks required in passive optical networks, has been added.

Behzad Razavi
April 2012

About the Author

Behzad Razavi is an award-winning teacher, researcher, and author. He holds a PhD from Stanford University and is 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.

Prof. Razavi 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, and the best paper award at the IEEE Custom Integrated Circuits Conference in 1998. 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. He was also recognized as one of the top 10 authors in the 50-year history of ISSCC. For his pioneering contributions to high-speed communication circuits, Prof. Razavi received the IEEE Donald Pederson Award in Solid-State Circuits in 2012.

Professor Razavi has served as an IEEE Distinguished Lecturer and is a Fellow of IEEE. He 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), and the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* and *Phase-Locking in High-Performance Systems.*

Chapter 1

Introduction to Optical Communications

The rapidly-growing volumes of data in telecommunication networks have rekindled interest in high-speed optical and electronic devices and systems. With the proliferation of the Internet and the rise in the speed of microprocessors and memories, the transport of data continues to be the bottleneck, motivating work on faster communication channels.

The idea of using light as a carrier for signals has been around for more than a century, but it was not until the mid-1950s that researchers demonstrated the utility of the optical fiber as a medium for light propagation [1]. Even though early fibers suffered from a high loss, the prospect of guided transmission of light with a very wide modulation band ignited extensive research in the area of optical communications, leading to the practical realization of optical networks in the 1970s.

This chapter provides an overview of optical communications, helping the reader understand how the concepts introduced in subsequent chapters fit into the "big picture." We begin with a brief history and study a generic optical system, describing its principal functions. Next, we present the challenges in the design of modern optical transceivers. Finally, we review the state of the art and the trends in transceiver design.

1.1 Brief History

Attempts to "guide" light go back to the 1840s, when a French physicist named Jacque Babinet demonstrated that light could be "bent" along a jet of water. By the late 1800s, researchers had discovered that light could travel inside bent rods made of quartz. The "fiber" was thus born as a flexible, transparent rod of glass or plastic.

In 1954, Abraham van Heel of the Technical University of Delft (Holland) and Harold Hopkins and Narinder Kapany of the Imperial College (Britain) independently published the idea of using a bundle of fibers to transmit images. Around the same time, Brian O'Brien of the American Optical Company recognized that "bare" fibers lost energy to the surrounding air, motivating van Heel to enclose the fiber core in a coating and hence lower the loss. Fiber loss was still very high, about 1,000 dB/km, limiting the usage to endoscopy applications.

The introduction of the laser as an intense light source in the 1950s and 1960s played a crucial role in fiber optics. The broadband modulation capability of lasers offered great potential for carrying information, although no suitable propagation medium seemed available. In 1966, Charles Ko and Charles Hockem of the Standard Telecommunication Laboratory (Britain) proposed that the optical fiber could be utilized as a signal transmission medium if the loss was lowered to 20 dB/km. They also postulated that such a low loss would be obtained if the impurities in the fiber material were reduced substantially.

Four years later, Robert Mauer and two of his colleagues at Corning Glass Works demonstrated silica fibers having a loss of less than 20 dB/km. With advances in semiconductor industry, the art of reducing impurities and dislocations in fibers improved as well, leading to a loss of 4 dB/km in 1975 and 0.2 dB/km in 1979. The dream of carrying massive volumes of information over long distances was thus fulfilled: in 1977, AT&T and GTE deployed the first fiber optic telephone system.

The widespread usage of optical communication for the transport of high-speed data stems from (1) the large bandwidth of fibers (roughly 25 to 50 GHz) and (2) the low loss of fibers (0.15 to 0.2 dB/km). By comparison, the loss reaches 200 dB/km at 100 MHz for twisted-pair cables and 500 dB/km at 1 GHz for low-cost coaxial cables. Also, wireless propagation with carrier frequencies of several gigahertz incurs an attenuation of tens of decibels across a few meters while supporting data rates lower than 100 Mb/s.

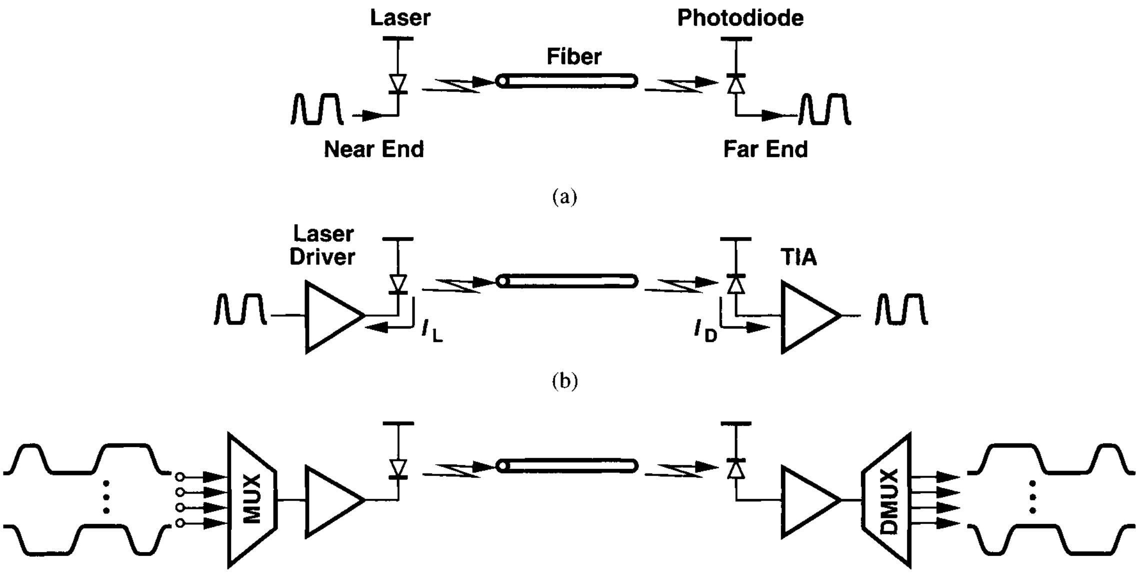
The large (and free) bandwidth provided by fibers has led to another important development: the use of multiple wavelengths (frequencies) to carry several channels on a single fiber. For example, it has been demonstrated that 100 wavelengths, each carrying data at 10 Gb/s, allow communication at an overall rate of 1 Tb/s across 400 km.

1.2 Generic Optical System

The goal of an optical communication (OC) system is to carry large volumes of data across a long distance. For example, the telephone traffic in Europe is connected to that in the United States through a fiber system installed across the Atlantic Ocean.

Depicted in Fig. 1.1(a), a simple OC system consists of three components: (1) an electro-optical transducer (e.g., a laser diode), which converts the electrical data to optical form (i.e., it produces light for logical ONEs and remains off for logical ZEROs); (2) a fiber, which carries the light produced by the laser; and (3) a photodetector (e.g., a photodiode), which senses the light at the end of the fiber and converts it to an electrical signal. We call the transmit and receive sides the "near end" and the "far end," respectively. As explained in Chapter 3, lasers are driven by electrical currents, and photodiodes generate an output current.

With long or low-cost fibers, the light experiences considerable attenuation as it travels from the near end to the far end. Thus, (1) the laser must produce a high light intensity, e.g., tens of milliwatts; (2) the photodiode must exhibit a high sensitivity to light; and (3) the electrical signal generated by the photodiode must be amplified with low noise. These observations lead to the more complete system shown in Fig. 1.1(b), where a "laser driver" delivers large currents to the laser and a "transimpedance amplifier" (TIA) amplifies the photodiode output with low noise and sufficient bandwidth, converting it to a voltage. For



(c)

Figure 1.1 (a) Simple optical system, (b) addition of driver and amplifier, (c) addition of MUX and DMUX.

example, data at a rate of 10 Gb/s may be applied to the laser driver, modulate the laser light at a wavelength of 1.55 μm, and emerge at the output of the TIA with an amplitude of 10 mV.

The transmit and receive operations in Fig. 1.1(b) process high-speed "serial" data, e.g., a single stream of data at 10 Gb/s. However, the actual data provided to the transmitter (TX) is in the form of many low-speed channels ("parallel" data) because it is generated by multiple users. The task of parallel-to-serial conversion is performed by a "multiplexer" (MUX). Similarly, the receiver (RX) must incorporate a "demultiplexer" (DMUX) to reproduce the original parallel channels. The resulting system is shown in Fig. 1.1(c).

The topology of Fig. 1.1(c) is still incomplete. Let us first consider the transmit end. The multiplexer requires a number of clock frequencies with precise edge alignment. These clocks are generated by a phase-locked loop (PLL). Furthermore, in practice, the MUX output suffers from nonidealities such as "jitter" and "intersymbol interference" (ISI), mandating the use of a "clean-up" flipflop before the laser driver. These modifications lead to the transmitter illustrated in Fig. 1.2(a).

The receive end also requires additional functions. Since the TIA output swing may not be large enough to provide logical levels, a high-gain amplifier (called a "limiting amplifier") must follow the TIA. Moreover, since the received data may exhibit substantial noise, a clean-up flipflop (called a "decision circuit") is interposed between the limiting amplifier and the DMUX. The receiver thus appears as shown in Fig. 1.2(b).

The receiver of Fig. 1.2(b) lacks a means of generating the clock necessary for the de-

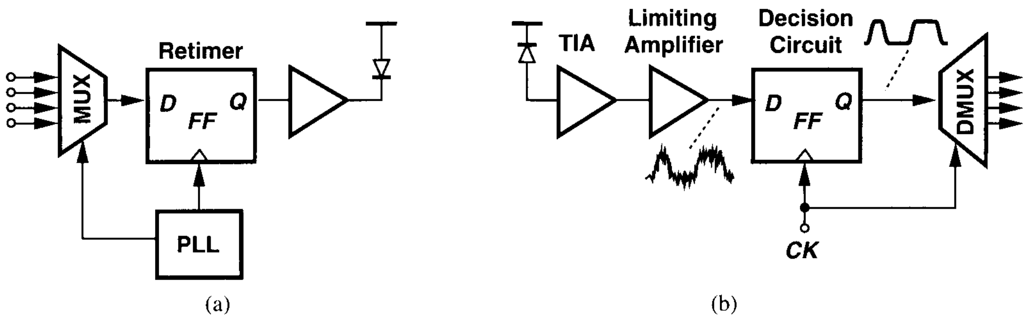


Figure 1.2 Modified (a) transmitter and (b) receiver.

cision circuit and the DMUX. This clock must bear a well-defined phase relationship with respect to the received data so that the flipflop samples the high and low levels "optimally," i.e., at the midpoint of each bit. The task of generating such a clock from the incoming data is called "clock recovery." The overall operation of clock recovery and data cleanup is called "clock and data recovery" (CDR). Figure 1.3 shows the complete system. Note that the laser driver incorporates power control (Chapter 10) and the TIA employs automatic gain control (AGC) (Chapter 4).

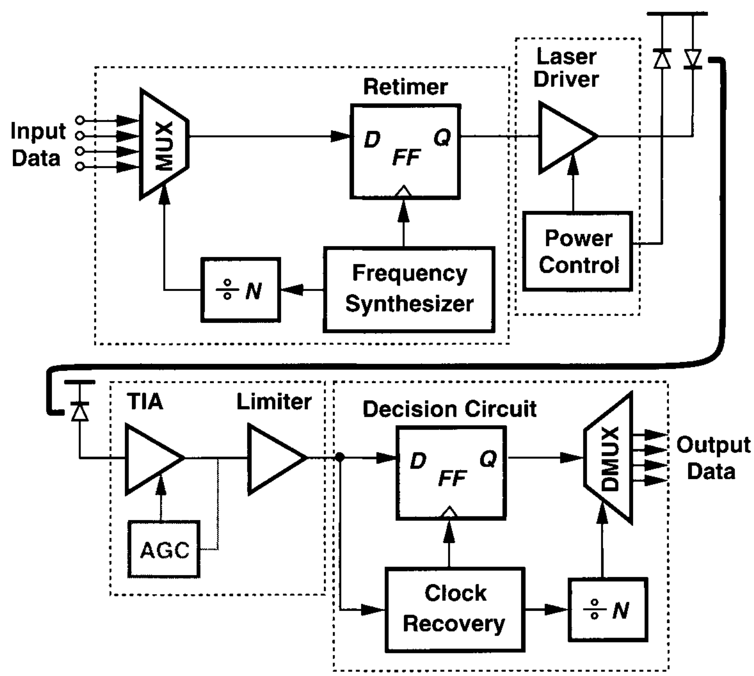


Figure 1.3 Complete system.

1.3 Design Challenges

While the system topology of Fig. 1.3 has not changed much over the past several decades, the design of its building blocks and the levels of integration have. Motivated by the evolution and affordability of IC technologies as well as the demand for higher performance, this change has created new challenges, necessitating new circuit and architecture techniques. We review some of the challenges here.

The transmitter of Fig. 1.3 entails several issues that manifest themselves at high speeds and/or in scaled IC technologies. Since the jitter of the transmitted data is determined primarily by that of the PLL, a robust, low-noise design with high supply and substrate rejection becomes essential. Furthermore, the design of skew-free multiplexers proves difficult at high data rates.

Another critical challenge arises from the laser driver, a circuit that must deliver tens of milliamperes of current with very short rise and fall times. Since laser diodes may experience large voltage swings between on and off states, the driver design becomes more difficult as scaled technologies impose lower supply voltages. The package parasitics also severely limit the speed with which such high currents can be switched to the laser [2].

The optical components in Fig. 1.3, namely, the laser diode, the fiber, and the photodiode, introduce their own nonidealities, requiring close interaction between electronic and optical design. Effects such as chirp, dispersion, attenuation, and efficiency play a major role in the overall link budget.

The receiver of Fig. 1.3 also presents many problems. The noise, gain, and bandwidth of the TIA and the limiter directly impact both the sensitivity and the speed of the overall system, raising additional issues as the supply voltage scales down. Moreover, the clock and data recovery functions must provide a high speed, tolerate long runs (sequences of identical bits), and satisfy stringent jitter and bandwidth requirements.

Full integration of the transceiver shown in Fig. 1.3 on a single chip raises a number of concerns. The high-speed digital signals in the MUX and DMUX may corrupt the receiver input or the oscillators used in the PLL and the CDR circuit. The high slew rates produced by the laser driver may lead to similar corruptions and also desensitize the TIA. Finally, since the oscillators in the transmit PLL and the receive CDR circuit operate at slightly different frequencies (with the difference given by the mismatch between the crystal frequencies in two communicating transceivers), they may "pull" each other, generating substantial jitter.

The above issues have resulted in multichip solutions that integrate the noisy and sensitive functions on different substrates. The dashed boxes in Fig. 1.3 indicate a typical partitioning, suggesting the following single-chip blocks: the PLL/MUX circuit (also called the "serializer"), the laser driver along with its power control circuitry, the TIA/limiter combination, and the CDR/MUX circuit (also called the "deserializer"). Recent work has integrated the serializer and deserializer (producing a "SERDES") but the TX and RX amplifiers may remain in isolation.

1.4 State of the Art

The new optical revolution is reminiscent of the monumental change that radio-frequency (RF) design began to experience in the early 1990s. This resurgence entails three important trends: (1) Modular, general-purpose building blocks are gradually replaced by end-to-end solutions that benefit from device/circuit/architecture codesign. (2) Greater levels of integration on a single chip provide higher performance and lower cost. (3) Mainstream VLSI technologies such as CMOS and BiCMOS continue to take over the territories thus far claimed by GaAs and InP devices. Modern OC transceiver applications continue to challenge designers along many dimensions.

Realization in CMOS Technology The cost and integration advantages of CMOS technology have motivated extensive work on high-speed CMOS design. Issues such as noise, speed, voltage headroom, and substrate coupling pose many difficulties in the design of CMOS transceivers. Research on 10-Gb/s CMOS CDR circuits yielded results in 2000 [3], and CMOS serializers and deserializers operating at this rate were reported in 2002 [4, 5].

Speed With the increasing volume of data transported in the backplane of the Internet, optical communication at rates of 40 Gb/s has become attractive. Such high speeds emerge as a new territory for IC design because prior work at these frequencies ("millimeter-wave frequencies") has been limited to narrowband, low-complexity circuits for wireless applications. Pushing bipolar and, preferably, CMOS technologies to such speeds, designers must cope with broadband characterization of active and passive devices, transmission-line behavior of on-chip interconnects, and high-speed packaging issues. A 40-Gb/s SiGe CDR circuit has been reported in [6].

Level of Integration Integrating a complete SERDES on a single CMOS chip serves as the first step toward much greater sophistication in OC transceiver design. Two important trends particularly suited to CMOS technology are: (1) integration of the SERDES along with the large digital processor that interfaces with the network (the "framer"); such integration eliminates a large number of high-speed printed-circuit board (PCB) lines between the two, simplifying the package design and saving substantial power. (2) integration of multiple SERDES on one chip; since the total data rate can be increased through the use of multiple light *wavelengths* on a single fiber, an important thrust is to integrate several SERDES on the same substrate, thereby increasing the "port density."

Power Dissipation At high speeds and/or high port densities, the power dissipation of optical transceivers becomes critical as it determines the type and size of the package in which the entire module is housed. Today's 10-Gb/s SERDES consume about 1 W of power, leading to serious packaging issues if four must be integrated on one chip. Interestingly, the low supply voltage required for deep-submicron CMOS technologies does reduce the overall power dissipation (e.g., in the output buffers) while making circuit design more difficult.

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CHAPTER 2

Basic Concepts

This chapter forms the background necessary for the analysis and design of optical communication circuits and systems. We first review the properties of random binary data and consider methods of generating pseudo-random sequences. Next, we study the effect of bandwidth limitation and noise on random data. Finally, we introduce the concepts of phase noise and jitter and review transmission lines.

2.1 Properties of Random Binary Data

Most optical communication systems employ simple binary amplitude modulation of the lightwave for ease of detection. The random binary sequence (RBS) experiences various imperfections in the optical and electrical domains, raising important design issues. In this section, we study properties of random data to the extent necessary for circuit and system analysis.

A random binary sequence consists of logical ONEs and ZEROs that carry the information and usually occur with equal probabilities [Fig. 2.1(a)]. If each bit period is T_b seconds, we say the bit rate, R_b, is equal to $1/T_b$ bits per second.[1] The sequence depicted

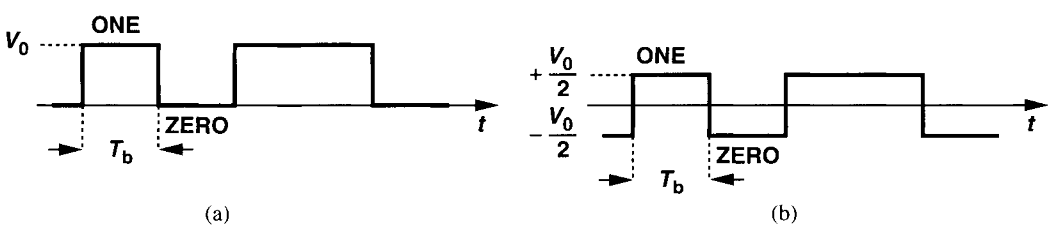

Figure 2.1 Random binary sequence with (a) finite and (b) zero dc content.

in Fig. 2.1(a) contains a nonzero average value because the logical ZEROs are represented

[1] We use b/s for random data and Hz for periodic waveforms, e.g., clocks.

by a zero voltage (or current). In some cases, it is simpler to view the waveform as shown in Fig. 2.1(b), where the ONEs and ZEROs assume equal and opposite values, thereby yielding a zero average.

The random nature of data implies that a binary sequence may contain arbitrarily long strings of consecutive ONEs or ZEROs (also called "runs") (Fig. 2.2). We say the data

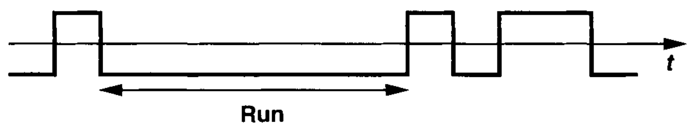

Figure 2.2 Random binary sequence with long run.

exhibits a low "transition density." Such strings create difficulties in the design of many optical transceiver circuits. In particular, operations such as ac coupling, offset cancellation, and clock recovery are sensitive to low transition densities, failing completely if a run becomes arbitrarily long. For this reason, optical communication standards typically specify the maximum "run length,"[2] i.e., the maximum number of consecutive ONEs or ZEROs allowed in the data. A typical run may be as long as 72 bits. To avoid exceeding such a run length, the data is encoded properly in the transmitter.

It is also instructive to examine random binary data in the frequency domain. How is the spectrum of a random sequence obtained?[3] Let us represent the random binary sequence by

$$x(t) = \sum_k b_k p(t - kT_b), \tag{2.1}$$

where $b_k = \pm 1$ and $p(t)$ denotes the pulse shape. That is, the RBS is viewed as positive and negative replicas of a basic pulse that are repeated every T_b seconds (Fig. 2.3). While we can assume that $p(t)$ is simply a rectangular pulse of width T_b, it is still useful to obtain

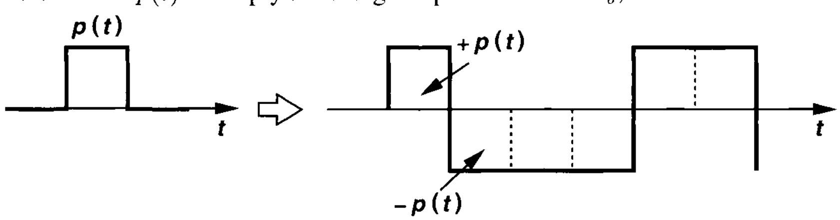

Figure 2.3 Random sequence viewed as random repetition of a pulse.

the spectrum of $x(t)$ for an arbitrary $p(t)$.

[2] Also called "consecutive identical digits" (CIDs).

[3] The spectrum of a waveform indicates how much power the signal carries in a 1-Hz bandwidth at each frequency.

It can be proved that, if the positive and negative pulses in (2.1) occur with equal probabilities, then the power spectral density of $x(t)$ is given by

$$S_x(f) = \frac{1}{T_b}|P(f)|^2, \tag{2.2}$$

where $P(f)$ represents the Fourier transform of $p(t)$ [1]. Equation (2.2) reveals many interesting properties of various data formats used in communications. As we will see throughout this book, many of these properties directly impact the design of transceivers.

Let us now compute $S_x(f)$ if $p(t)$ is a rectangular pulse T_b seconds wide and repeated every T_b seconds. Since the Fourier transform of such a pulse is equal to

$$P(f) = T_b \frac{\sin(\pi f T_b)}{\pi f T_b}, \tag{2.3}$$

the spectrum of the random sequence is expressed as

$$S_x(f) = T_b \left[\frac{\sin(\pi f T_b)}{\pi f T_b}\right]^2. \tag{2.4}$$

Noting that $\sin(\pi f T_b)$ vanishes at $f = n/T_b$ for integer values of n, we construct the spectrum as shown in Fig. 2.4(a). To show a wider magnitude range of $S_x(f)$, it is common

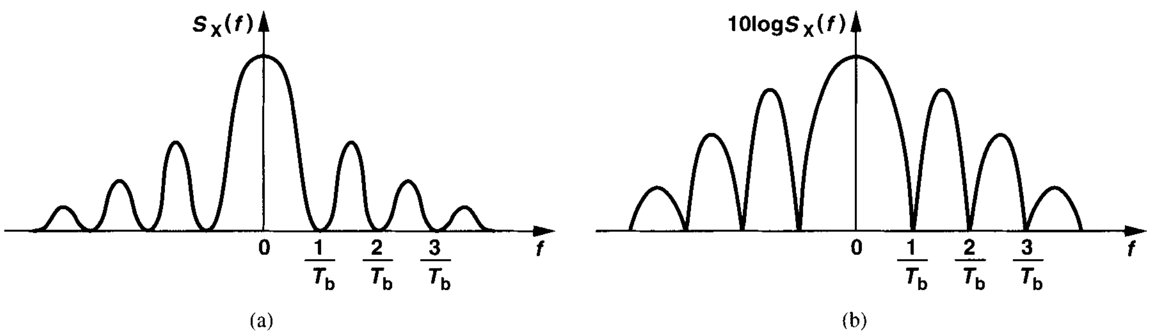

Figure 2.4 Spectrum of random binary data with (a) linear and (b) logarithmic vertical scale.

to use a logarithmic scale for the vertical axis [Fig. 2.4(b)].

The above analysis yields an important attribute of random binary sequences. For a bit rate of $1/T_b$, the spectrum exhibits no power at frequencies equal to $1/T_b$, $2/T_b$, etc. In other words, if the waveform is applied to a 1-Hz bandpass filter centered at $f = 1/T_b, 2/T_b, \cdots$, very little energy is observed. For example, a 10-Gb/s sequence does not contain a 10-GHz component [Fig. 2.5(a)]. This somewhat surprising result is better understood if we note that the fastest waveform at 10 Gb/s consists of a 1010 sequence with each bit 100 ps wide [Fig. 2.5(b)]. Such a signal is a 5-GHz square wave, containing only odd harmonics at 5 GHz, 15 GHz, etc. Another method of proving the existence of the nulls is described in Section 2.2.