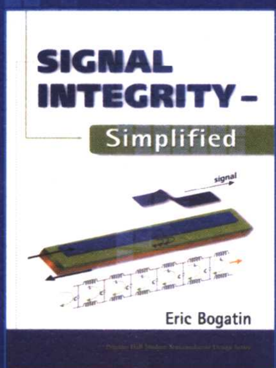
国外电子与通信教材系列

英文版

# 信号完整性分析

# Signal Integrity: Simplified




[美] Eric Bogatin 著

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# 信号完整性分析 英文版

## Signal Integrity: Simplified

本书全面论述了信号完整性问题。它以入门式的切入方式，使读者很容易认识到物理互连影响电气性能的实质，从而可以尽快掌握信号完整性设计技术。本书作者从实践的角度指出了造成信号完整性问题的根源，特别给出了在设计前期阶段的问题解决方案。

**本书的主要内容**

- 信号完整性和物理设计概论
- 带宽、电感和特性阻抗的实质意义
- 电阻、电容、电感和阻抗的相关分析
- 解决信号完整性问题的四个实用技术手段：经验法则、解析近似、数值模拟和实际测量
- 物理互连设计对信号完整性的影响
- 数学推导背后隐藏的解决方案
- 改进信号完整性推荐的设计准则

本书中文版


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通常，大多数同类书籍都会花费大量篇幅进行严格的理论推导和数学描述，而本书则更强调直观理解、实用工具和工程实践。

## 作者简介

**Eric Bogatin**：于1976年获麻省理工学院物理学士学位，并于1980年获亚利桑那大学物理硕士和博士学位。目前是GigaTest实验室的首席技术主管（CTO）。多年来，他在信号完整性领域，包括基本原理、测量技术和分析工具等方面举办过许多短期课程，培训过4000多名工程师，在信号完整性、互连设计、封装技术等领域已发表了100多篇技术论文、专栏文章和专著。

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国外电子与通信教材系列

# 信号完整性分析

## （英文版）

# Signal Integrity: Simplified

［美］Eric Bogatin 著

電子工業出版社
**Publishing House of Electronics Industry**
北京 · BEIJING

## 内容简介

本书全面论述了信号完整性问题。主要讲述了信号完整性和物理设计概论，带宽、电感和特性阻抗的实质含义，电阻、电容、电感和阻抗的相关分析，解决信号完整性问题的四个实用技术手段，物理互连设计对信号完整性的影响，数学推导背后隐藏的解决方案，以及改进信号完整性推荐的设计准则等。该书与其他大多数同类书籍相比更强调直观理解、实用工具和工程实践。它以入门式的切入方式，使读者很容易认识到物理互连影响电气性能的实质，从而可以尽快掌握信号完整性设计技术。本书作者以实践专家的视角指出了造成信号完整性问题的根源，特别给出了在设计前期阶段的问题解决方案。

这是面向电子工业界的设计工程师和产品负责人的一本具有实用价值的参考书，其目的在于帮助他们在信号完整性问题出现之前能提前发现并及早加以解决，同时也可作为相关专业本科生及研究生的教学指导用书。



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# 序

2001年7月间，电子工业出版社的领导同志邀请各高校十几位通信领域方面的老师，商量引进国外教材问题。与会同志对出版社提出的计划十分赞同，大家认为，这对我国通信事业、特别是对高等院校通信学科的教学工作会很有好处。

教材建设是高校教学建设的主要内容之一。编写、出版一本好的教材，意味着开设了一门好的课程，甚至可能预示着一个崭新学科的诞生。20世纪40年代MIT林肯实验室出版的一套28本雷达丛书，对近代电子学科、特别是对雷达技术的推动作用，就是一个很好的例子。

我国领导部门对教材建设一直非常重视。20世纪80年代，在原教委教材编审委员会的领导下，汇集了高等院校几百位富有教学经验的专家，编写、出版了一大批教材；很多院校还根据学校的特点和需要，陆续编写了大量的讲义和参考书。这些教材对高校的教学工作发挥了极好的作用。近年来，随着教学改革不断深入和科学技术的飞速进步，有的教材内容已比较陈旧、落后，难以适应教学的要求，特别是在电子学和通信技术发展神速、可以讲是日新月异的今天，如何适应这种情况，更是一个必须认真考虑的问题。解决这个问题，除了依靠高校的老师和专家撰写新的符合要求的教科书外，引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，是会有好处的。

一年多来，电子工业出版社为此做了很多工作。他们成立了一个“国外电子与通信教材系列”项目组，选派了富有经验的业务骨干负责有关工作，收集了230余种通信教材和参考书的详细资料，调来了100余种原版教材样书，依靠由20余位专家组成的出版委员会，从中精选了40多种，内容丰富，覆盖了电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等方面，既可作为通信专业本科生和研究生的教学用书，也可作为有关专业人员的参考材料。此外，这批教材，有的翻译为中文，还有部分教材直接影印出版，以供教师用英语直接授课。希望这些教材的引进和出版对高校通信教学和教材改革能起一定作用。

在这里，我还要感谢参加工作的各位教授、专家、老师与参加翻译、编辑和出版的同志们。各位专家认真负责、严谨细致、不辞辛劳、不怕琐碎和精益求精的态度，充分体现了中国教育工作者和出版工作者的良好美德。

随着我国经济建设的发展和科学技术的不断进步，对高校教学工作会不断提出新的要求和希望。我想，无论如何，要做好引进国外教材的工作，一定要联系我国的实际。教材和学术专著不同，既要注意科学性、学术性，也要重视可读性，要深入浅出，便于读者自学；引进的教材要适应高校教学改革的需要，针对目前一些教材内容较为陈旧的问题，有目的地引进一些先进的和正在发展中的交叉学科的参考书；要与国内出版的教材相配套，安排好出版英文原版教材和翻译教材的比例。我们努力使这套教材能尽量满足上述要求，希望它们能放在学生们的课桌上，发挥一定的作用。

最后，预祝“国外电子与通信教材系列”项目取得成功，为我国电子与通信教学和通信产业的发展培土施肥。也恳切希望读者能对这些书籍的不足之处、特别是翻译中存在的问题，提出意见和建议，以便再版时更正。

吴佑寿

中国工程院院士、清华大学教授

“国外电子与通信教材系列”出版委员会主任

# 出 版 说 明

进入21世纪以来，我国信息产业在生产和科研方面都大大加快了发展速度，并已成为国民经济发展的支柱产业之一。但是，与世界上其他信息产业发达的国家相比，我国在技术开发、教育培训等方面都还存在着较大的差距。特别是在加入WTO后的今天，我国信息产业面临着国外竞争对手的严峻挑战。

作为我国信息产业的专业科技出版社，我们始终关注着全球电子信息技术的发展方向，始终把引进国外优秀电子与通信信息技术教材和专业书籍放在我们工作的重要位置上。在2000年至2001年间，我社先后从世界著名出版公司引进出版了40余种教材，形成了一套“国外计算机科学教材系列”，在全国高校以及科研部门中受到了欢迎和好评，得到了计算机领域的广大教师与科研工作者的充分肯定。

引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，将有助于我国信息产业培养具有国际竞争能力的技术人才，也将有助于我国国内在电子与通信教学工作中掌握和跟踪国际发展水平。根据国内信息产业的现状、教育部《关于“十五”期间普通高等教育教材建设与改革的意见》的指示精神以及高等院校老师们反映的各种意见，我们决定引进“国外电子与通信教材系列”，并随后开展了大量准备工作。此次引进的国外电子与通信教材均来自国际著名出版商，其中影印教材约占一半。教材内容涉及的学科方向包括电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等，其中既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。我们还将与国外出版商一起，陆续推出一些教材的教学支持资料，为授课教师提供帮助。

此外，“国外电子与通信教材系列”的引进和出版工作得到了教育部高等教育司的大力支持和帮助，其中的部分引进教材已通过“教育部高等学校电子信息科学与工程类专业教学指导委员会”的审核，并得到教育部高等教育司的批准，纳入了“教育部高等教育司推荐——国外优秀信息科学与技术系列教学用书”。

为做好该系列教材的翻译工作，我们聘请了清华大学、北京大学、北京邮电大学、南京邮电大学、东南大学、西安交通大学、天津大学、西安电子科技大学、电子科技大学、中山大学、哈尔滨工业大学、西南交通大学等著名高校的教授和骨干教师参与教材的翻译和审校工作。许多教授在国内电子与通信专业领域享有较高的声望，具有丰富的教学经验，他们的渊博学识从根本上保证了教材的翻译质量和专业学术方面的严格与准确。我们在此对他们的辛勤工作与贡献表示衷心的感谢。此外，对于编辑的选择，我们达到了专业对口；对于从英文原书中发现的错误，我们通过与作者联络、从网上下载勘误表等方式，逐一进行了修订；同时，我们对审校、排版、印制质量进行了严格把关。

今后，我们将进一步加强同各高校教师的密切关系，努力引进更多的国外优秀教材和教学参考书，为我国电子与通信教材达到世界先进水平而努力。由于我们对国内外电子与通信教育的发展仍存在一些认识上的不足，在选题、翻译、出版等方面的工作中还有许多需要改进的地方，恳请广大师生和读者提出批评及建议。

电子工业出版社

# 教材出版委员会

# 导　读

本书作者Eric Bogatin具有20多年从事信号完整性研究、进行互连设计和开展工程师培训的经验。作者在书中以独特的工程视角和入门式的切入方式揭示了信号完整性问题的根源，帮助读者尽可能在电子设计的初期找到信号完整性问题的解决方案。本书是他在信号完整性领域的一部力作，特色鲜明、可读性强，主要的读者对象是电子设计工程师。

信号完整性是指信号电压(电流)完美的波形形状及质量。由于物理互连造成的干扰和噪声，使连线上信号的波形外观变差，出现了非正常形状的变形，称为信号完整性被破坏。信号完整性问题是物理互连在高速情况下的直接结果。

物理互连包括芯片内连线、芯片封装、PCB模块及电子系统连接等，它们极大地影响高速时的互连信号和电源分布网络的质量。当系统时钟大于100 MHz或者数字信号上升边小于1 ns时，物理互连可能对电路系统和数据传输造成不同程度甚至颠覆性的后果。

凸现的信号完整性问题迫使人们采用新的设计方法学和新的策略，从产品概念创建到设计完成阶段采用新技术应对信号完整性问题。新技术的内涵是：采用分析技术与工具，对芯片和系统设计进行建模、仿真以及辅助测量，充分完成对信号完整性的设计和验证。

按照通常的说法，信号完整性分为芯片和PCB/封装两个着眼点。两者原理上相通，但技术上有别，本书着眼的重点则是在PCB及IC封装设计上。该书从信号完整性的角度介绍工程师们既熟悉又新鲜的基本概念，将时域、频域、阻抗匹配、电阻、电容、电感、传输线、介质材料、差分技术等内容由浅入深地娓娓道来，将读者引入信号完整性研究的新天地。本书将电路互连对系统性能的影响归结为四类噪声问题：反射、串扰、轨道塌陷以及EMI；倾心推介了四种信号完整性研究分析途径：经验法则、解析近似、数值仿真和实际测量。全书用尽量少的笔墨进行了理论描述和数学推导，极力突出直观概念和工程实用性。

当前，电子系统与电路全面进入1 GHz以上的高速高频设计领域。在实现VLSI芯片、PCB和系统集成设计功能的前提下，具有性能属性的信号完整性问题已经成为电子设计的一个瓶颈。国外在理论研究、工程实践和EDA软件方面都有很多建树。国内对信号完整性的研究也逐渐呈现出浓厚的热情，有了一定的基础。而对于大多数电子设计工程师来说，仍迫切需要一本系统性的实用教材。本书较适合于国内读者的需要，可以胜任这一角色。因此，我们将此书推荐给从事电子设计理论研究和工程开发的人员，从事信号完整性研究以及对信号完整性有兴趣的工程技术和管理人员。通过本书的学习，读者可以比较轻

松地了解电气性能的实质和物理互连对信号完整性的影响，能够尽快掌握信号完整性设计技术。

我们已于2004年组织翻译了本书并由电子工业出版社出版。依据在翻译过程及采用中文版施教期间的仔细考证，在本书中已更正了原作者的一些计算数据和公式推导中的错误。与中译本相对照，原著的出版将有助于推动国内在SI的知识掌握方面和国际前沿充分接轨。

李玉山
西安电子科技大学
电路CAD研究所

In physical science the first essential step in the direction of learning any subject is to find principles of numerical reckoning and practicable methods for measuring some quality connected with it. I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be.

Lord Kelvin (1824-1907)

# Preface

Printed circuit-board and IC-package design used to be a field that involved expertise in layout, CAD, logic design, heat transfer, mechanical engineering, and reliability analysis. With modern digital electronic systems pushing beyond the 1-GHz barrier, packaging and board designers must now balance signal integrity and electrical performance with these other concerns.

Everyone who touches the physical design of a product has the potential of affecting the performance. All designers should understand how what they do will affect signal integrity or, at the very least, be able to talk with engineers who are responsible for the signal integrity.

The old design methodology of building prototypes, hoping they work, and then testing them to find out is no longer cost effective when time to market is as important as cost and performance. If signal integrity is not taken into account from the beginning, there is little hope a design will work the first time.

In our new "high-speed" world, where the packaging and interconnect are no longer electrically transparent to the signals, a new methodology for designing a product right the first time is needed. This new methodology is based on predictability. The first step is to use established design guidelines based on engineering discipline. The second step is to evaluate the expected performance by "putting in the numbers." This is what distinguishes engineering from guesswork. It takes advantage of four important tools: rules of thumb, analytic approximations, numerical simulation tools, and measurements. With an efficient design and simulation process, many of the trade-offs between the expected performance and the ultimate cost can be evaluated early in the design cycle, where the time, risk, and cost savings will have the biggest impact. The way to solve signal integrity problems is to first understand their origin and then apply all the tools in our toolbox to find and verify the optimum solution.

The design process is an intuitive one. The source of inspiration for a new way of solving a problem is that mysterious world of imagination and creativity. An idea is generated and the analytical powers of our technical training take over to massage the idea into a practical solution. Though computer simulations are absolutely necessary for final verification of a solution, they only rarely aid in our intuitive understanding. Rather, it is an understanding of the mechanisms, principles and definitions, and exposure to the possibilities, that contribute to the creation of a solution. Arriving at that initial guess and knowing the places to look for solutions require understanding and imagination.

This book emphasizes the intuitive approach. It offers a framework for understanding the electrical properties of interconnects and materials that apply across the entire hierarchy from on-chip, through the packages, circuit boards, connectors, and cables.

Those struggling with the confusing and sometimes contradictory statements made in the trade press will use this book as their starting place. Those experienced in electrical design will use this book as the place to finally understand what the equations mean.

In this book, terms are introduced starting at the ground floor. For example, the impedance of a transmission line is the most fundamental electrical property of an interconnect. It describes what a signal will see electrically and how it will interact with the interconnects. For those new to signal integrity, most of the problems arise from confusion over three terms: the *characteristic* impedance, *the* impedance, and the *instantaneous* impedance a signal sees. This distinction is even important for experienced engineers. This book introduces the reader to each of these terms and their meanings, without complex mathematics.

New topics are introduced at a basic level; most are not covered in other signal integrity books at this level. These include partial inductance (as distinct from loop inductance), the origin of ground bounce and EMI, impedance, transmission line discontinuities, differential impedance, and attenuation in lossy lines affecting the collapse of the eye diagram. These topics have become critically important for the new high-speed serial links.

In addition to understanding the basic principles, leveraging commercially available tools is critical for the practicing engineer who wants to find the best answer in the shortest time. Tools for solving signal integrity problems fall in two categories: analysis and characterization. Analysis is what we usually refer to as a calculation. Characterization is what we usually refer to as a measurement. The various tools, guidelines on when they should be used, and examples of their value are presented throughout the book.

There are three types of analysis tools: rules of thumb, analytic approximations, and numerical simulation. Each has a different balance between accuracy and effort to use. Each has a right and a wrong place for its appropriate use. And each tool is important and should be in the toolbox of every engineer.

Rules of thumb, such as "the self inductance of a wire is about 25 nH/inch," are important when having a quick answer NOW! is more important than having an accurate answer late. With very few exceptions, every equation used in signal integrity is either a definition or an approximation. Approximations are great for exploring design space and balancing design and performance trade-offs. However, without knowing how accurate a particular approximation really is, would you want to risk a $10,000 board-fabrication run and four weeks of your schedule based on an approximation?

When accuracy is important, for example, when signing off on a design, numerical simulation is the right tool to use. In the last five years, a whole new generation of tools has become available. These new tools have the powerful combination of being both easy to use and accurate. They can predict the characteristic impedance, cross talk, and differential impedance of any cross-section transmission line and simulate how a signal might be affected by any type of termination scheme. You don't have to be a Ph.D. to use this new generation of tools so there is no reason every engineer can't take advantage of them.

The quality of the simulation is only as good as the quality of the electrical description of the components (i.e., the equivalent circuit models). Engineers are taught about circuit models of gates that perform all the information processing, but rarely are the circuit models of the interconnects reviewed. Fifteen years ago, when interconnects looked transparent to the signals, all interconnects were considered as ideal wires—no impedance and no delay. When these terms were added, they were lumped together as "parasitics."

Today, in a high-speed digital system with a clock frequency above about 100 MHz, it is the real wires—the wire bonds, the package leads, the pins, the circuit board traces, the connectors, and the cabling—that create signal-integrity problems and can prevent products from working correctly the first time. Understanding these "analog" effects, designing for them, specifying correct values for them, and including them in the system simulations before the design is committed to hardware, can enable moving a more robust product to market more quickly.

This book provides the tools to enable all engineers and managers involved in chip packaging and board, connector and interconnect design, to understand how these passive elements affect the electrical performance of a system and how they can be incorporated in system simulation. It illustrates how to perform engineering estimates of important electrical parameters and evaluate technology trade-offs. Examples are selected from a wide variety of common systems, including on-chip interconnects, wire bonds, flip chip attach, multilayer circuit boards, DIPs, PGAs, BGAs, QFPs, MCM connectors, and cables.

While most textbooks emphasize theoretical derivation and mathematical rigor, this book emphasizes intuitive understanding, practical tools, and engineering discipline. We use the principles of electrical engineering and physics and apply them to the world of packaging and interconnects to establish a framework of understanding and a methodology of solving problems. The tools of time- and frequency-domain measurement, two- and three-dimensional field solvers, transmission-line simulations, circuit simulators, and analytical approximations are introduced to build verified equivalent circuit models for packages and interconnects.

There are two important questions that all designers should ask of any model they use: How accurate is it? And what is the bandwidth of the model? The answers to these questions can come only from measurements. Measurements play the very important role of risk reduction.

The three generic measurement instruments, the impedance analyzer, the vector-network analyzer (VNA) and the time-domain reflectometer (TDR) are introduced and the interpretation of their data explained. Examples of measurements from real interconnects such as IC packages, printed circuit boards, cables, and connectors are included throughout this book to illustrate the principles and, by example, the value of characterization tools.

This book has been designed for use by people of all levels of expertise and training: engineers, project managers, sales and marketing managers, technology developers, and scientists. We start out with an overview of why designing the interconnects for high-speed digital systems is difficult and what major technical hurdles must be overcome to reach high-frequency operation.

We apply the tools of electrical engineering and physics to the problems of signal integrity in digital signals through the entire range of interconnects. The concept of equivalent circuit models is introduced to facilitate the quantified prediction of performance. The rest of the book describes how the circuit models of interconnects affect the electrical performance of the system in terms of the four families of noise problems: reflections, cross talk, rail collapse in the power distribution network, and EMI.

This book originated from a series of short courses and semester-long courses the author gave to packaging, circuit-board, and design engineers. It is oriented to all people who need to balance electrical performance with all other packaging and interconnect concerns in their system designs. This book provides the foundation to understand how the physical design world of geometries and material properties affects electrical performance.

If you remember nothing else about signal integrity, you should remember the following important general principles. These are summarized here and described in more detail throughout this book.

## Top Ten Signal Integrity Principles

1. The key to efficient high-speed product design is to take advantage of analysis tools that enable accurate performance prediction. Use measurements as a way of validating the design process, reducing risk, and increasing confidence in the design tools.

2. The only way to separate myth from reality is to put in the numbers using rules of thumb, approximations, numerical simulation tools, or measurements. This is the essential element of engineering discipline.

3. Each interconnect is a transmission line with a signal and a return path, regardless of its length, shape, or signal rise time. A signal sees an instantaneous impedance at each step along its way down an interconnect. Signal quality is dramatically improved if the instantaneous impedance is constant, as in a transmission line with a uniform cross section.

4. Forget the word *ground*. More problems are created than solved by using this term. Every signal has a return path. Think *return path* and you will train

your intuition to look for and treat the return path as carefully as you treat the signal path.

5. Current flows through a capacitor whenever the voltage changes. For fast edges, even the air gap between the edge of a circuit board and a dangling wire can have a low impedance through the fringe field capacitance.
6. Inductance is fundamentally related to the number of magnetic-field line loops completely surrounding a current. If the number of field line loops ever changes, for whatever reason, a voltage will be created across the conductor. This is the origin of some reflection noise, cross talk, switching noise, ground bounce, rail collapse, and some EMI.
7. Ground bounce is the voltage created on the ground return conductor due to changing currents through the total inductance of the return path. It is the primary cause of switching noise and EMI.
8. The bandwidth of a signal is the highest sine-wave frequency component that is significant, compared to an equivalent frequency square wave. The bandwidth of a model is the highest sine-wave frequency at which the model still accurately predicts the actual performance of the interconnect. Never use a model in an application where the signal bandwidth is higher than the model's bandwidth.
9. Never forget, with few exceptions, every formula used in signal integrity is either a definition or an approximation. If accuracy is important, do not use an approximation.
10. The problem caused by lossy transmission lines is the rise-time degradation. The losses increase with frequency due to skin depth and dielectric losses. If the losses were constant with frequency, the rise time would not change and lossy lines would be only a minor inconvenience.
11. The most expensive rule is the one that delays the product ship.

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