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Semiconductor Devices for High-Speed Optoelectronics

Providing an all-inclusive treatment of electronic and optoelectronic devices used in high-speed optical communication systems, this book emphasizes circuit applications, advanced device design solutions, and noise in sources and receivers. Core topics covered include semiconductors and semiconductor optical properties, high-speed circuits and transistors, detectors, sources, and modulators. It discusses in detail both active devices (heterostructure field-effect and bipolar transistors) and passive components (lumped and distributed) for high-speed electronic integrated circuits. It also describes recent advances in high-speed devices for 40 Gbps systems. Introductory elements are provided, making the book open to readers without a specific background in optoelectronics, whilst end-of-chapter review questions and numerical problems enable readers to test their understanding and experiment with realistic data.

Giovanni Ghione is Full Professor of Electronics at Politecnico di Torino, Torino, Italy. His current research activity involves the physics-based and circuit-oriented modeling of high-speed electronic and optoelectronic components, with particular attention to III-N power devices, thermal and noise simulation, electrooptic and electroabsorption modulators, coplanar passive components, and integrated circuits. He is a Fellow of the IEEE and has authored or co-authored over 200 technical papers and four books.

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To the memory of my parents

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Preface

The development of high-speed fiber-based optical communication systems that has taken place since the early 1970s can be really considered as a technological wonder. In a few years, key components were devised (such as the semiconductor laser) with the help of novel technological processes (such as epitaxial growth) and found immediate application thanks to the development of low-loss optical fibers. New compound semiconductor alloys (namely, InGaAsP) were ready to provide their potential to emit the right wavelengths needed for long-haul fiber propagation. When electronic repeaters seemed unable to provide a solution to long-haul propagation, fiber amplifiers were developed that allowed for all-optical signal regeneration. And the list could be continued. A miracle of ingenuity from a host of researchers made it possible to assemble this complex puzzle in a few years, thus bringing optoelectronic technology to a consumer electronics level.

Increasing the system capacity by increasing the transmission speed was, of course, a main concern from the early stages of optical system development. While optoelectronic devices behave, on the electronic side, in a rather conventional way up to speeds of the order of 1 Gbps, for larger speeds (up to 40 Gbps and beyond) RF wave propagation has to be accounted for in designing and modeling optoelectronic devices. When speed increases, the distributed interaction between RF and optical waves becomes a useful, sometimes indispensable, ingredient in many optoelectronic devices, like modulators and (to a lesser extent) detectors. Similarly, the electronic circuits that interface light sources, modulators, and detectors should provide broadband operation up to microwave or millimeter-wave frequencies, thus making it mandatory to exploit compound semiconductor electronics (GaAs- or InP-based) or advanced Si-based solutions (like SiGe HBT integrated circuits or nanometer MOS processes).

Increasing speed beyond the 10 Gbps limit by improving device performance, however interesting it is from the research and development side, may in practice be less appealing from the market standpoint. The ultimate destiny of optoelectronic devices (such as sources, modulators, and detectors) optimized for 40 Gbps (or even faster) systems after the post-2000 market downturn still is uncertain, and research in the field has followed alternative paths to the increase of system capacity. At the same time, new application fields have been developed, for instance in the area of integrated all-Si optical signal processing systems, and also for integrated circuit level high-capacity communications. However, the development of high-speed optoelectronic devices has raised a number of stimulating (and probably lasting) design issues. An example is the

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principle of the distributed interaction between optical and RF waves, which is common to a variety of high-speed components. Another relevant theme is the co-design and the (possibly monolithic) integration of the electronic and optoelectronic components of a system, not to mention the critical aspects concerning device packaging and interconnection in systems operating at 40 Gbps and beyond.

Taking the above into account, it is not surprising that the main purpose of the present book is to provide a kind of unified (or, perhaps, not too widely separated) treatment of high-speed electronics and optoelectronics, starting from compound semiconductor basics, down to high-speed transistors, ICs, detectors, sources and modulators. Part of the material was originally developed for a number of postgraduate and Master courses, and therefore has the ambition (but also the limitation) of providing a treatment starting from the very basics. It is hoped that this justifies both the presence of introductory material on semiconductors and semiconductor optical properties, and a treatment of high-speed electronics starting from a review of transmission lines and scattering parameters. From this standpoint, the text attempts to be as self-contained as possible. Of course, the choice of subjects is somewhat influenced by the author's personal tastes and previous research experience (not to mention the need to keep the page count below 500): some emphasis has been put on noise, again with an attempt to present a self-contained treatment of this rather difficult topic, and many important optoelectronic components have not been included (to mention one, semiconductor optical amplifiers). Yet another innovative subject that is missing is microwave photonics, where of course the RF and microwave and optoelectronic worlds meet. Nevertheless, the text is (in the author's opinion, at least) different enough from the many excellent textbooks on optoelectronics available on the market to justify the attempt to write it.

I wish to thank a number of colleagues (from Politecnico di Torino, unless otherwise stated) for their direct or indirect contribution to this book. Ivo Montrosset provided many useful suggestions on the treatment of optical sources. Incidentally, it was under the guidance of Ivo Montrosset and Carlo Naldi that (then an undergraduate student) I was introduced to the basics of passive and active optoelectronic devices, respectively; this happened, alas, almost 30 years ago. Helpful discussions with Gian Paolo Bava and Pierluigi Debernardi (Consiglio Nazionale delle Ricerche) on laser noise, with Simona Donati Guerrieri on the semiconductor optical properties and with Fabrizio Bonani and Marco Pirola on active and passive high-speed semiconductor electronic devices and circuits are gratefully acknowledged. Michele Goano kindly revised the sections on compound semiconductors and the numerical problems, and provided useful suggestions on III-N semiconductors. Federica Cappelluti prepared many figures (in particular in the section on photodetectors), initially exploited in lecture slides. Finally, Claudio Coriasso (Avago Turin Technology Center, Torino) kindly provided material on integrated electroabsorption modulators (EAL), including some figures. Additionally, I am indebted to a number of ME students who cooperated in research, mainly on lithium niobate modulators; among those, special mention goes to F. Carbonera, D. Frassati, G. Giarola, A. Mela, G. Omegna, L. Terlevich, P. Zandano. A number of PhD students also worked on subjects relevant to the present book: Francesco Bertazzi (now with Politecnico di Torino) on EM modeling of distributed electrooptic structures; Pietro Bianco,

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on high-speed modulator drivers; Federica Cappelluti, on electroabsorption modulator modeling; Gloria Carvalho, on EAL modeling; Antonello Nespola (now with Istituto Superiore Mario Boella), on the modeling of distributed high-speed photodetectors. Part of the thesis work of Antonello Nespola and Federica Cappelluti was carried out within the framework of a cooperation with UCLA (Professor Ming Wu, now at University of California, Berkeley). Finally, I gratefully recall many helpful discussions with colleagues from the industry: among those, Marina Meliga, Roberto Paoletti, Marco Romagnoli, and Luciano Socci.

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