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K. Schneider
H. Zimmermann

Highly Sensitive Optical Receivers

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Highly Sensitive Optical Receivers

With 191 Figures and 25 Tables

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Dipl.-Ing. Dr. techn. Kerstin Schneider
Univ. Professor Dr.-Ing. Horst Zimmermann
Institute for Electrical Measurements and Circuit Design, Vienna University of Technology
Gusshausstr. 25/354, A-1040 Wien, Austria
E-Mail: kerstin.schneider@tuwien.ac.at, horst.zimmermann@ieee.org

Series Editors:
Dr. Kiyoo Itoh
Hitachi Ltd., Central Research Laboratory, 1-280 Higashi-Koigakubo
Kokubunji-shi, Tokyo 185-8601, Japan

Professor Thomas Lee
Stanford University, Department of Electrical Engineering, 420 Via Palou Mall, CIS-205
Stanford, CA 94305-4070, USA

Professor Takayasu Sakurai
Center for Collaborative Research, University of Tokyo, 7-22-1 Roppongi
Minato-ku, Tokyo 106-8558, Japan

Professor Willy M. C. Sansen
Katholieke Universiteit Leuven, ESAT-MICAS, Kasteelpark Arenberg 10
3001 Leuven, Belgium

Professor Doris Schmitt-Landsiedel
Technische Universität München, Lehrstuhl für Technische Elektronik
Theresienstrasse 90, Gebäude N3, 80290 München, Germany

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Preface

The growing demand for high-speed, broadband data communication motivates the development of low-cost, high-performance optical receivers for fiber-optical networks. This book sets its focus especially on highly sensitive receivers with medium and high speed capability for the "last mile" connection in fiber-to-the-home (FTTH) systems. These connections are normally realized with infrared light with wavelengths of 1310 and 1540 nm. This fact makes it necessary for silicon optical receivers to use an external Ge or III/V-semiconductor based photodiode. Therefore this book deals with optical receivers for detection of infrared light, including all the problems emerging from an external photodiode, such as very high input-node capacitance somewhere in the order of pF, compared to an integrated photodiode where the input-node capacitance is about an order of magnitude less, problems due to bond-wire parasitics at the input-node, etc. The influence of these problems can be clearly seen in the performance of optical receivers. The high input-node capacitance, for example, strongly influences the bandwidth and the sensitivity.

Compared to the book *Integrated Silicon Optoelectronics* of one of the authors, which concentrates on physics and integration of photodetectors in modern silicon bipolar, CMOS and BiCMOS processes, descriptions of fabrication technologies and properties of integrated photodetectors, and *Silicon Optoelectronic Integrated Circuits*, which goes deeper into the details of the circuit design of ICs with integrated photodiodes for a wide variety of applications, this book concentrates on circuit design for optical receivers with external photodiodes for optical communication. The main subject of *Highly Sensitive Optical Receivers* is the description of the state-of-the-art of low-noise silicon amplifiers and the comparison of bipolar, CMOS, BiCMOS, as well as SiGe amplifiers.

This new book is a summary of fundamental theory and a presentation of state-of-the-art optical receiver circuits and designs. Recent optical receivers developed by the authors show the rapid progress in optical receiver design.

The first chapter explains the motivation why all optical receivers designed by the authors are done in deep-sub-micron CMOS technology.

Although these deep-sub-micron CMOS technologies cause a lot of problems, due to low power supply voltage, low Early voltage and so on, this book will show that these technologies are attractive and interesting for low-noise optical receivers for medium and high data rate applications.

In particular, the newest deep-sub-micron CMOS low-noise amplifier topologies are described in detail addressing the challenging application in optical burst-mode receivers. Thereby the excellent noise properties of deep-sub-micron CMOS receivers and fast gain switching capability are highlighted. A new approach for solving the stability problem resulting from gain switching is described. This book shows how to solve the difficulties in circuit design with deep-sub-micron CMOS technologies and how to use the benefits of the technology as for example the possibility to easily integrate the analog and the digital part in systems-on-chip (SoCs). Using a standard digital deep-sub-micron CMOS process for analog design has the disadvantage of high device tolerances to deal with, but avoids costs for technology development for analog process extensions.

In the beginning of the book in Chap. 1 the motivation for burst-mode communication and the incentive to use systems-on-chip in deep-sub-micron CMOS technology are discussed.

In Chap. 2 different kinds of networks are described. Furthermore continuous-mode and burst-mode access are compared. The additional requirements for burst-mode optical receivers will be discussed and the advantages of time-division-multiplex access (TDMA) will be pointed out. The increasing importance of burst-mode receivers is reflected in the growing amount of publications on this topic. In the beginning of the 1990s the first papers on burst-mode receivers were published. The number rapidly increased in the following years and is still growing. In Chap. 2, fundamental parts of optical receiver front-ends are also described. An essential part of optical receivers are the photodetectors. Photodetectors and especially SiGe photodetectors, therefore, are discussed in Chap. 3. The main focus of attention is on the preamplifier, being usually a transimpedance amplifier, in Chap. 4. Nevertheless, also main and limiting amplifiers are discussed.

Chapter 5 gives a short overview of an SiGe heterojunction bipolar technology, as well as some more details about the deep-sub-micron CMOS processes used for the designs described in Chap. 9.

AC-analysis as well as stability analysis of several designs are contained in Chap. 6. After the feedback theory a transimpedance amplifier with an ideal amplifier is described. This is followed by an analysis of realized circuits.

Afterwards, in Chap. 7, integrated circuit technologies of current interest are described. BiCMOS, SiGe heterojunction bipolar, submicron CMOS and deep-sub-micron CMOS technologies are compared and the advantages and disadvantages of each concerning noise are described. The device properties are compared to the properties of ideal devices and the effects of down-scaling technologies are described.

In Chap. 8 an overview of the state of the art of BiCMOS, SiGe heterojunction-bipolar and CMOS optical receivers in the literature is given. Chapter 9 summarizes the simulation environment and component models for circuit design and describes the measurement set-up and the circuits as well as printed circuit boards for characterization. Afterwards the circuits and properties of several advanced optical CMOS receivers and optical burst-mode receivers designed at the Institute for Electrical Measurements and Circuit Design at Vienna University of Technology in 0.18 μm and 0.12 μm standard digital CMOS are described in detail. Finally a summary of the characterized performance of the optical receivers is done. A comparison of the different designs and their results for optical receivers known from the literature follows.

The authors would like to thank their colleagues at the Institute for Electrical Measurements and Circuit Design at Vienna University of Technology for fruitful discussion and their valuable support, especially Franz Schlögl, Robert Swoboda, Michael Förtsch, Jürgen Leeb and Alexander Nemecek as well as the head of the institute, Gottfried Magerl, for his great support towards a quick start of research. Furthermore special thanks are directed to A. Wiesbauer, J. Hauptmann, M. Haas, and A. Martin from Infineon Technologies DC Villach and DC Vienna for their constant financial and technical support as well as the opportunity to use the design environment.

Vienna, June 2006

Kerstin Schneider
Horst Zimmermann

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Vienna, June 2006

Kerstin Schneider

Contents

List of Symbols

Symbol	Description	Units
A	Area	mm^2
A_0	Low-frequency open-loop gain	
$A(f)$	Frequency-dependent gain	
A_{loop}	Loop gain	
$A_{3I}(f)$	Frequency-dependent gain of three-inverter amplifier	
$A_{FC}(f)$	Frequency-dependent gain of folded-cascode circuit	
A_{TIA}	Effective transimpedance of TIA	Ω
c	Speed of light in a medium	$cm\,s^{-1}$
c_0	Speed of light in vacuum	$cm\,s^{-1}$
C_F	Feedback capacitance	F
C_{gd}	Gate–drain capacitance	F
C_{gs}	Gate–source capacitance	F
C_j	Junction capacitance	F
C_{ox}	Gate oxide capacitance per unit area	$fF/\mu m^2$
C_{pd}	Photodiode capacitance	F
C_{para}	Parasitic capacitance	F
C_T	Input-node capacitance	F
d_{ARC}	Thickness of antireflecting coating	µm
d_I	Thickness of intrinsic region	µm
d_p	Thickness of p-type region	µm
F	Lowering factor for stability analysis	
f	Frequency	Hz
$f_{-3\,dB}$	-3 dB cut-off frequency	Hz
f_β	-3 dB cut-off frequency of β	Hz
f_g	-3 dB frequency bandwidth	Hz

Symbol	Description	Units
g_{ds}	Transistor output conductance	$\mathrm{A\,V^{-1}}$
g_{m}	Transconductance	$\mathrm{A\,V^{-1}}$
$g_{\mathrm{m}}^{\mathrm{I}}$	Transconductance of inverter	$\mathrm{A\,V^{-1}}$
h	Plack constant	Js
$\hbar$	$h/2\pi$	Js
$\langle i_0 \rangle$	Mean photocurrent for logical zero	A
$\langle i_1 \rangle$	Mean photocurrent for logical one	A
i_{L}	Leakage current of photodiode	A
$\overline{i^2}$	Spectral noise current density	$\mathrm{A^2}$
$\overline{i_{\mathrm{o}}^2}$	Spectral noise output noise current density	$\mathrm{A^2\,Hz^{-1}}$
$\overline{i_{\mathrm{b}}^2}$	Base current noise source	$\mathrm{A^2}$
$\overline{i_{\mathrm{c}}^2}$	Collector current noise source	$\mathrm{A^2}$
$\overline{i_{\mathrm{d}}^2}$	Drain current noise source	$\mathrm{A^2}$
$\overline{i_{\mathrm{g}}^2}$	Gate current noise source	$\mathrm{A^2}$
$i_{\mathrm{c}}x$	Small-signal capacitance current of stage x	A
i_{o}	Small-signal output current	A
i_{rx}	Small-signal resistance current of stage x	A
$\overline{i_{\mathrm{n,R}}^2}$	Spectral resistor noise current density	$\mathrm{A^2\,Hz^{-1}}$
$\overline{i_{\mathrm{n,in}}^2}$	Equivalent input noise current density	$\mathrm{A^2\,Hz^{-1}}$
$\overline{i_{\mathrm{n,amp}}^2}$	Equivalent input noise current density of amplifier	$\mathrm{A^2\,Hz^{-1}}$
$\overline{i_{\mathrm{n,Ti}}^2}$	Equivalent input noise current density of transistor	$\mathrm{A^2\,Hz^{-1}}$
I	Current	A
I_{in}	Input current	A
I_{ph}	Photocurrent	A
I_{B}	Base current	A
I_{C}	Collector current	A
I_{D}	Drain current	A
I_{E}	Emitter current	A
I_{S}	Source current	A
k_{B}	Boltzmann constant	$\mathrm{J\,K^{-1}}$
$k_{\mathrm{B}}T$	Thermal energy	eV
L	Length	µm
L_{B}	Inductance of bond wire	H
L_{D}	Diffusion length	nm
$\overline{n}$	Refractive index	
$\overline{n_1}$	Refractive index of fiber core	
$\overline{n_2}$	Refractive index of fiber cladding	
$\overline{n_{\mathrm{ARC}}}$	Refractive index of antireflecting coating	
$\overline{n_{\mathrm{s}}}$	Refractive index of surroundings	
$\overline{n_{\mathrm{sc}}}$	Refractive index of semiconductor	

Symbol	Description	Units
P_{char}	Characteristic polynomial	
P_{opt}	Incident optical power	W
$p_0(i)$	Probability density for a logical zero	
$p_1(i)$	Probability density for a logical one	
$\overline{P_{\mathrm{opt}}}$	Average incident optical power	W
q	Magnitude of electronic charge	As
$\overline{R}$	Reflectivity	
r_{b}	Base series resistance	Ω
r_{c}	Small-signal collector series resistance	Ω
r_{o}	Small-signal output resistance	Ω
r_{d}	Small-signal drain series resistance	Ω
r_{s}	Small-signal source series resistance	Ω
r_{DS}	Small-signal output resistance	Ω
R	Responsivity	$\mathrm{A\,W^{-1}}$
R_{F}	Feedback resistance	Ω
R_{S}	Series resistance	Ω
R_{L}	Load resistance	Ω
S	Spacing	µm
t	Time	s
t_{f}	Fall time	s
t_{r}	Rise time	s
T	Absolute temperature	K
T_{p}	Period interval	s
$\overline{v_{\mathrm{b}}^2}$	Base resistor noise voltage	$\mathrm{V^2}$
$\overline{v_{\mathrm{R}}^2}$	Spectral resistor noise voltage density	$\mathrm{V^2\,Hz^{-1}}$
$\overline{v_{\mathrm{n,amp}}^2}$	Equivalent input noise voltage density of amplifier	$\mathrm{V^2\,Hz^{-1}}$
$\overline{v_{\mathrm{n,in}}^2}$	Equivalent input noise voltage density	$\mathrm{V^2\,Hz^{-1}}$
$\overline{v_{\mathrm{n,Ti}}^2}$	Equivalent input noise voltage density of transistor	$\mathrm{V^2\,Hz^{-1}}$
V	Voltage	V
V_{BE}	Base–emitter voltage	V
V_{br}	Breakdown voltage	V
V_{DS}	Drain–source voltage	V
V_{Early}	Early voltage	V
V_{GS}	Gate–source voltage	V
V_{pin}	Photodiode voltage	V
V_{T}	Thermal voltage $k_{\mathrm{B}}\mathrm{T\,q^{-1}}$	V
V_{Th}	Threshold voltage	V
V_{o}	Output voltage	V
W	Width	µm
Z_{F}	Feedback impedance of transimpedance amplifier	Ω