

Integrated Silicon-based Optical Modulators

100 Gb/s and Beyond

Integrated Silicon-based Optical Modulators

100 Gb/s and Beyond

Kensuke Ogawa

SPIE PRESS

Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Names: Ogawa, Kensuke, author.

Title: Integrated silicon-based optical modulators : 100 Gb/s and beyond /
Kensuke Ogawa.

Description: Bellingham, Washington, USA : SPIE Press, [2019] | Includes
bibliographical references and index.

Identifiers: LCCN 2018048725 (print) | LCCN 2019003000 (ebook) | ISBN
9781510625822 (pdf) | ISBN 9781510625839 (epub) | ISBN 9781510625846
(mobi) | ISBN 9781510625815 | ISBN 9781510625815 (softcover) | ISBN
151062581X (softcover)

Subjects: LCSH: Light modulators. | Silicon–Optical properties. | Integrated
optics.

Classification: LCC TK8360.L5 (ebook) | LCC TK8360.L5 O33 2019 (print) | DDC
621.381/045–dc23

LC record available at <https://lcn.loc.gov/2018048725>

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: books@spie.org

Web: <http://spie.org>

Copyright © 2019 Society of Photo-Optical Instrumentation Engineers
(SPIE)

All rights reserved. No part of this publication may be reproduced or
distributed in any form or by any means without written permission of the
publisher.

The content of this book reflects the work and thought of the author. Every effort
has been made to publish reliable and accurate information herein, but the
publisher is not responsible for the validity of the information or for any
outcomes resulting from reliance thereon.

Printed in the United States of America.

First Printing.

For updates to this book, visit <http://spie.org> and type “PM302” in the
search field.

SPIE.

Table of Contents

<i>Preface</i>	<i>ix</i>
<i>Glossary of Terms</i>	<i>xi</i>
1 Introduction	1
References	6
2 Background	9
2.1 High-Capacity Optical Networks	9
2.1.1 Overview	9
2.1.2 Basic elements	9
2.1.3 Transmission capacity	12
2.1.4 Energy efficiency	12
2.2 Optical Modulators in High-Capacity Optical Networks	13
2.2.1 Optical modulator in optical transmitter	13
2.2.2 Semiconductor optical modulators	15
2.2.3 Integrated optical modulators on silicon-photonics platforms	17
References	19
3 Introduction to Integrated Optical Modulators	25
3.1 Classification of Optical Modulators	25
3.1.1 Electro-absorption optical modulators	25
3.1.2 Ring-resonator optical modulator using electro-refraction effects	27
3.1.3 Mach-Zehnder optical modulator using electro-refraction effects	28
3.2 High-Speed Broadband Mach-Zehnder Optical Modulators	31
3.2.1 Mach-Zehnder interferometer with RF electrodes	31
3.2.2 High-contrast intensity modulation	34
3.2.3 High-Q phase modulation	37
3.3 Integrated Silicon-Based Mach-Zehnder Optical Modulators	39
3.3.1 Optical-waveguide elements	39
3.3.2 Monolithic modulator on chip	40
3.3.3 Fabrication processes	42
References	43

4	Optical Circuits and Waveguides in Integrated Mach–Zehnder Optical Modulators	51
4.1	Optical Circuits	52
4.1.1	Single Mach–Zehnder optical modulator	52
4.1.2	Quadrature Mach–Zehnder optical modulator	53
4.1.3	Polarization-division-multiplexed Mach–Zehnder optical modulator	54
4.2	Transfer-Matrix Framework	55
4.2.1	Representation in transfer matrices	55
4.2.2	Transfer matrices of Mach–Zehnder optical modulators	56
4.3	Optical Waveguide and Optical Mode	58
4.3.1	Guided wave in ray trace	58
4.3.2	Mode field and wave propagation	61
4.4	Optical Waveguide Features	65
4.4.1	Channel and rib waveguides	65
4.4.2	Optical splitter/coupler	71
4.4.3	Polarization-division multiplexer	74
4.4.4	Other building blocks based on optical waveguides	78
	References	79
5	Electronic and Opto-electronic Properties of High-Speed Phase Shifters	85
5.1	Physics in Phase Modulation	85
5.1.1	Pockels effect	85
5.1.2	Intraband free-carrier plasma dispersion and Drude model	87
5.1.3	Interband dipole transition processes	93
5.1.4	Spectral and thermal characteristics	97
5.1.5	Frequency chirping	99
5.2	Classification of Phase Shifters using Free-Carrier Plasma Dispersion	100
5.2.1	Lateral PN-junction phase shifter	100
5.2.2	Vertical PN-junction phase shifter	102
5.2.3	Other types of phase shifter	104
5.3	Design and Modeling of PN-Junction Phase Shifters	104
5.3.1	Semi-analytical method	104
5.3.2	Computational method	111
5.3.3	Equivalent-circuit model	117
5.3.4	Remarks on designing traveling-wave electrodes	120
	References	121
6	Optical, Electrical, and Electro-Optical Characteristics of Integrated Silicon-based Optical Modulators	133
6.1	DC Optical Characteristics	133
6.1.1	Optical loss	133
6.1.2	Phase shift and chromatic dispersion	142

6.2	DC Electrical Characteristics	149
6.2.1	Current-voltage characteristics	149
6.2.2	Microscopic imaging of the PN junction	152
6.3	RF Frequency Characteristics	153
6.3.1	S-parameter characteristics	153
6.3.2	Effect of parasitics	155
6.4	Transient Characteristics	156
6.4.1	Response limitation by RC time constant	156
6.4.2	Intensity modulation characteristics at various modulation speeds	157
6.4.3	Intensity modulation characteristics at high temperatures	159
6.4.4	Phase modulation characteristics and chirp parameter	160
	References	161
7	Transmission Characteristics of Integrated Silicon-Based Optical Modulators	169
7.1	Applications in Optical Network Domains at 100 Gb/s and Beyond	169
7.2	On–Off Keying and Pulse Amplitude Modulation	171
7.2.1	Apparatus and device for OOK transmission	171
7.2.2	Characteristics of OOK transmission	173
7.2.3	PAM n scheme	176
7.3	Phase-Shift Keying	177
7.3.1	Apparatus and device for PSK transmission	177
7.3.2	Characteristics of PSK transmission	181
7.4	Polarization-Division-Multiplexed Quadrature Phase-Shift Keying	184
7.4.1	Apparatus and device for PDM IQ transmission	184
7.4.2	Characteristics of PDM IQ transmission	186
7.5	Discrete Multi-Tone Scheme	189
7.5.1	Apparatus for DMT transmission	189
7.5.2	Characteristics of DMT transmission	189
7.6	Note on Transmission Characteristics	190
	References	191
8	Photonic–Electronic Integration with Silicon-Based Optical Modulators	199
8.1	Integration with Electronic and Photonic Devices	199
8.1.1	Monolithic integration	199
8.1.2	Wafer-bonding integration: silicon on silicon	201
8.1.3	Die-bonding integration: III-V on silicon	201
8.1.4	Hybrid integration	204
8.1.5	Optical coupling and packaging	205
8.2	Integration of Optical Performance Monitoring	211
8.2.1	Technical background	211
8.2.2	Conventional approach	212

8.2.3	Optical layout for integration	213
8.2.4	Photonic integrated performance-monitoring circuit	216
8.2.5	All-silicon performance monitoring	218
	References	219
Appendix		227
A.1	Bit Rates and Modulation Formats in High-Capacity Optical Networks	227
A.1.1	Bit rates	227
A.1.2	Formats in intensity modulation	227
A.1.3	Formats in phase modulation	228
A.1.4	Format in sub-carrier modulation	231
A.2	Kramers–Kronig Transformation	232
A.2.1	General principle	232
A.2.2	Computational method	233
	References	234
	<i>Index</i>	235

Preface

With the advent of semiconductor diode lasers that emit a coherent light beam under current injection and low-loss silica optical fibers that transmit a light beam over long distances, the technology of optical communications became practically available in the late 1960s to the early 1970s. Since then, optical communications have grown ceaselessly over the decades and have nowadays become indispensable for a variety of networks, such as 5G mobile communication, social networking, video streaming, the Internet of Things, artificial intelligence, virtual/augmented reality, and large-scale simulation. The data transmission capacity (measured in bit rate per wavelength channel, which is allocated in a single core of silica optical fiber) was ~ 10 Mb/s in the 1970s and a few Gb/s in the 1980s. This capacity has reached 100 Gb/s and beyond in modern optical communications—an increase of more than four orders of magnitude, or roughly ten times per decade from the dawn of optical communications.

Such remarkable growth of data traffic in optical communications was enabled by the progress of high-speed photonic devices that are capable of processing and transmitting optical signals at the bit rates cited above. Photonic integration technologies provide design and fabrication platforms that facilitate the high-density integration of various elements of photonic devices with small footprints. These platforms thereby allow the manufacture of small-form-factor photonic assemblies that consist of photonic integrated circuits. Among these platforms, silicon-photonics platforms are most suited to the design and fabrication of photonic integrated circuits with low power consumption and cost because the platforms are based on electronic design tools and fabrication process lines developed for high-volume manufacturing of silicon integrated circuits that consist of ultra-low-voltage complementary metal–oxide–semiconductor devices. Therefore, there is increasing interest in the research and development of photonic integrated circuits on silicon-photonics platforms to accommodate the demand for versatile and affordable small-form-factor optical equipment in high-volume applications such as intra- and inter-datacenter optical communications around the world.

This book focuses on high-speed, integrated silicon-based optical modulators as the cutting-edge, key photonic device at the forefront of

modern optical-communication equipment. A high-speed optical modulator allows electrical-to-optical conversion in an optical transmitter for optical signal generation in advanced modulation formats with complex intensity- and phase- modulation schemes at bit rates of 100 Gb/s and beyond per wavelength channel. Silicon-photonics platforms allow integration of entire elements on chip to miniaturize the high-speed optical modulator within a footprint less than 1 cm². The following chapters describe the basic principles to the latest developments of integrated silicon-based optical modulators. It is hoped that this book will inspire readers to further enhancements of modulator performance and sophistication of photonic integration technology, including diode lasers to realize ultra-compact, high-speed integrated optical transmitters in the next generation of optical communications.

Kensuke Ogawa
February 2019

Glossary of Terms

ADC	Analog-to-digital converter
AOC	Active optical cable
APD	Avalanche photodiode
ASE	Amplified spontaneous emission
ASK	Amplitude-shift keying
BER	Bit error rate
BOX	Buried oxide
BPF	Bandpass filter
BPM	Beam propagation method
BPSK	Binary phase-shift keying
CFP	C form-factor pluggable
CMOS	Complementary metal–oxide–semiconductor
CPW	Coplanar waveguide
CVD	Chemical vapor deposition
CW	Continuous wave
DAC	Digital-to-analog converter
DC	Direct current
DCF	Dispersion compensation fiber
DCI	Datacenter interconnect
DEMUX	Wavelength demultiplexing
DML	Directly modulated laser
DP-QPSK	Dual-polarization quadrature phase-shift keying
DPSK	Differential phase-shift keying
DQPSK	Differential quadrature phase-shift keying
DSP	Digital signal processor
EDFA	Erbium-doped fiber amplifier
EML	Externally modulated laser
E-O	Electrical-optical
ER	Extinction ratio
FDTD	Finite-difference time domain
FEC	Forward error correction
FEM	Finite-element method

FIR	Finite impulse response
FK	Franz–Keldysh
FOM	Figure of merit
FTTH	Fiber-to-the-home
I	In phase
IC	Integrated circuit
IM-DD	Intensity modulation and direct detection
I/O	Input and output
IP	Internet protocol
IQ	In phase and quadrature phase
LAN	Local-area network
LD	Laser diode
LN	Lithium niobate
LO	Local oscillator
MEMS	Micro-electro-mechanical systems
MFC	Mode-field converter
MMI	Multi-mode interferometer
MOS	Metal–oxide–semiconductor
MUX	Wavelength multiplexing
MZI	Mach-Zehnder interferometer
NRZ	Non-return to zero
OOK	On–off keying
OSNR	Optical signal-to-noise ratio
PAM n	Pulse amplitude modulation in n levels
PBC	Polarization-beam combiner
PCB	Printed circuit board
PD	Photodiode
PDK	Process design kit
PDM	Polarization-division multiplexing
PIC	Photonic integrated circuit
PMF	Polarization-maintaining single-mode fiber
PR	Polarization rotator
PRBS	Pseudo-random bit stream
PPG	Pulse pattern generator
Q	Quadrature
QAM	Quadrature amplitude modulation
QCSE	Quantum-confined Stark effect
QPSK	Quadrature phase-shift keying
QSFP	Quad small-form-factor pluggable
QW	Quantum well
RZ	Return to zero
SCM	Scanning capacitance microscopy
SEM	Scanning electron microscopy

SLD	Super-luminescent diode
SMF	Standard-dispersion single-mode fiber
SNR	Signal-to-noise ratio
SOI	Silicon on insulator
SW	Switch
TE	Transverse-electric
TEC	Thermo-electric cooling
TEM	Transmission electron microscopy
TIA	Trans-impedance amplifier
TM	Transverse-magnetic
TO	Thermo-optic
VIA	Vertical interconnect access
VOA	Variable optical attenuator
WDM	Wavelength-division multiplexing

