Integrated Silicon-based Optical Modulators

100 Gb/s and Beyond

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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 $\sim$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 cm^2. 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