Springer Series in Optical Sciences 194

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Benjamin J. Eggleton *Editors*

# All-Optical Signal Processing

## Data Communication and Storage Applications

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ISSN 0342-4111 ISSN 1556-1534 (electronic)
Springer Series in Optical Sciences
ISBN 978-3-319-14991-2 ISBN 978-3-319-14992-9 (eBook)
DOI 10.1007/978-3-319-14992-9

Library of Congress Control Number: 2015933154

Springer Cham Heidelberg New York Dordrecht London


Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

# Springer Series in Optical Sciences

Volume 194

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# Preface

Although it holds the promise for substantial processing speed improvements, in today's communication infrastructure optics remains largely confined to the signal transport layer, as it lags behind electronics as far as signal processing is concerned. This situation is bound to change in the near future as the tremendous growth of data traffic requires the development of new, energy efficient, and fully transparent all-optical networks for telecom and datacom applications. This book provides a comprehensive review of the state of the art of all-optical devices based on nonlinear optical materials for applications to optical signal processing. Contributors to this book present breakthrough solutions for enabling a pervasive use of optics in data communication and signal storage applications. The book content ranges from the development of innovative materials and devices, such as graphene and photonic crystal structures, to the use of nonlinear optical signal processing for secure quantum information processing, for increasing the transmission channel capacity, and for enhancing the performance of broadband radio frequency signal processing. The book is expected to benefit all researchers in the fields of optical communications, photonic devices for optical signal processing, nonlinear guided wave optics, quantum information processing, and microwave photonics, including senior undergraduate and postgraduate students and industry researchers.

Chapter 1 summarizes the recent progress in materials and structures for all-optical signal processing that employ either second- or third-order optical nonlinearities. The dominant choice for quadratic materials is provided by periodically poled lithium niobate waveguides. For cubic nonlinearities, the range of materials ranges from glasses to both active and passive semiconductor devices: a brief summary of the advantages and disadvantages of each class of materials and device structure is provided. In Chap. 2, recent advances in new nonsilicon CMOS-compatible platforms for nonlinear integrated optics are revised, focusing on Hydex glass and silicon nitride. The promising new platform of amorphous silicon is also briefly discussed. These material systems have opened up new functionalities such as on-chip optical frequency comb generation, ultrafast optical pulse generation, and measurement. Chapter 3 overviews the principles of optical switching devices, based on either optical or electrical control signals, which permit to avoid the necessity of electro-optic conversion. Discussed devices include nonlinear mode couplers and interferometers based on optical fibers, and integrated waveguides based on photonic crystal structures or surface wave interactions in novel materials such as graphene. Chapter 4 reviews the recent progress on using nonlinear optical fibers for optical pulse shaping in the temporal and spectral domains. Significant examples that are most relevant for applications include the synthesis of specialized temporal waveforms, the generation of ultrashort pulses, and optical supercontinuum.

Given the exponential growth rate of the total volume of data transported across the communication network, energy consumption, alongside increased information capacity, has become a critical driver in deploying new technologies. In addition to transponders at the end terminals of an optical network, certain signal processing functions, such as regeneration, format conversion, wavelength conversion, and arbitrary waveform generation, are often proposed. The following chapters of the book discuss how many of these intermediate functions may be performed all-optically, with the primary advantage of increased bandwidth and consequent resource sharing. In Chap. 5 the need, the general principles, and the approaches used for the all-optical regeneration of mainly phase encoded signals of differing levels of coding complexity are discussed. The key underpinning technology and the current state of the art of optical regeneration, including a historic perspective, are presented.

Chapter 6 presents the theory and experiments of photonic signal processing, logic operations, and computing. These functionalities take advantage of nonlinear processes with ultrafast response time to perform high speed operations either on analog or digital optical signals directly in the optical domain. Practical all-optical frequency generation and conversion requires highly efficient parametric interactions across a wide spectral band. Chapter 7 presents a new class of traveling wave parametric mixers for efficient, cavity-free frequency generation. Driven by continuous-wave seeds, these devices combine inherently more stable lasers with distributed noise inhibition in dispersion-managed parametric processes. The operating principles, the design methodology, and the performance limits of parametric mixers are discussed, together with applications to signal multicasting and ultrafast channel processing.

Optical pulse shaping techniques are an active area of research for increasing the spectral efficiency of optical modulation formats in dense wavelength division multiplexed (DWDM) transmissions, by avoiding interchannel and intersymbol interference. In Chap. 8 the main pulse shapes of interest are introduced, the different available techniques for their generation are presented, along with the associated signal multiplexing schemes, namely orthogonal frequency division multiplexing (OFDM) and Nyquist pulse modulation. The relative performances of electronic and optical signal processors for implementing Fourier transforms and Nyquist pulse generation are discussed.

As previously mentioned, energy saving will be a main driver for the transition from electronic to optical signal processing solutions. Chapter 9 describes advanced functionalities for optical signal processing with reduced energy consumption using optical time lenses. This approach permits broadband optical processing, which is also capable of handling many bits in a single operation. In this way, the processing energy is shared by the many bits, and the energy per bit is reduced. The basic functionality is serial-to-parallel conversion in a single time lens. Combining time lenses into telescopic arrangements allows for more advanced signal processing solutions, such as conversion of OFDM signals into DWDM-like signals, which can be separated passively, i.e., without additional energy consumption. The previously discussed signal processing functions may also be performed by using the very optoelectronic devices used in the transponders themselves, either including decision circuitry and/or forward error correction or as linear media converters. In Chap. 10, the performance and energy consumption of digital coherent transponders, linear coherent repeaters, and modulator-based pulse shaping/frequency conversion is analyzed, thus setting an important benchmark for the proposed all-optical implementations.

The exponential growth in demand for information transmission capacity requires a rethinking of the maximum or Shannon capacity of the fiber-optic communication channel, in the presence of fiber nonlinearity. Chapter 11 addresses the problem of estimating the Shannon capacity for nonlinear communication channels, and discusses the potential of different optical signal coding, transmission, and processing techniques to improve the information capacity and increase the system reach of fiber-optic links.

Information and communication technologies based on quantum optics principles may lead to greatly improved functionalities such as enhanced sensing, exponentially faster computing, and the secure transfer of information. Chapter 12 overviews techniques for the nonlinear optics-based encoding and fully secure transfer of information in a quantum communication optical network. Chapter 13 discusses how classical optical signal processing techniques can be extended to nonclassical entangled photon states, thus permitting unprecedented control of the time frequency correlations shared by these light quanta. Moreover, in Chap. 13 it is shown that quantum properties produce interesting effects that are not observable with classical fields. Examples include Fourier transform pulse shaping, which relies on programmable spectral filtering and electro-optic modulation, where the temporal phase or amplitude of the entagled photon state is manipulated by means of an electrical signal.

Chapter 14 discusses how nonlinear optical effects in photonic chip scale devices may be exploited for enhancing the performance of radio frequency (RF) signal processing in microwave photonics applications. Specific examples presented in Chap. 14 include frequency agile and high suppression microwave bandstop filters, general purpose programmable analog signal processors, and high performance active microwave filters. Finally, Chap. 15 presents recent advances in optical signal processing techniques for wireless RF signals. Specifically, Chap. 15 discusses photonic architectures for wideband analog signal processing, including RF beamforming, co-channel interference cancelation, and physical layer security.

Besides broadband operation, photonics offers reduced size, weight, and power, in addition to low transmission loss, rapid reconfigurability, and immunity to electromagnetic interference.

We would like to thank Dr. Claus E. Ascheron, Springer Executive Editor for Physics, for inviting us, during the 2013 Conference on lasers and electro-optics in Munich, Germany, to bring a volume on all-optical signal processing to a wider audience. We also acknowledge helpful comments and suggestions by Dr. Herbert Venghaus of the Fraunhofer Institute for Telecommunications, and Editor of the Springer Series in Optical Sciences. Last but not the least, we are most grateful to all colleagues who contributed to this book for their brilliant work and continued effort in bringing this project to reality.

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# Contents