Hideyuki Suzuki
Jun Tanida
Masanori Hashimoto *Editors*

Photonic Neural Networks with Spatiotemporal Dynamics

Paradigms of Computing and Implementation

OPEN ACCESS

Springer

Photonic Neural Networks with Spatiotemporal Dynamics

Hideyuki Suzuki · Jun Tanida ·
Masanori Hashimoto
Editors

Photonic Neural Networks with Spatiotemporal Dynamics

Paradigms of Computing and Implementation

Springer

Editors
Hideyuki Suzuki
Graduate School of Information Science and Technology
Osaka University
Osaka, Japan

Jun Tanida
Graduate School of Information Science and Technology
Osaka University
Osaka, Japan

Masanori Hashimoto
Department of Informatics
Kyoto University
Kyoto, Japan

ISBN 978-981-99-5071-3 ISBN 978-981-99-5072-0 (eBook)
https://doi.org/10.1007/978-981-99-5072-0

© The Editor(s) (if applicable) and The Author(s) 2024. This book is an open access publication.

Open Access This book is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.
The images or other third party material in this book are included in the book's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Paper in this product is recyclable.

Preface

Light is an excellent carrier of information with the ability to transmit signals at extraordinarily fast speeds, as exemplified by the global network of optical fibers. Moreover, its spatiotemporal properties suggest the capability to perform a variety of information processing and computation. Optical computing technologies have been demonstrated to uniquely achieve high-speed, parallel, and massive computation, which is becoming increasingly important in the era of the smart society. Accordingly, optical computing is expected to serve as a crucial foundation for future information technologies.

Artificial neural network models, such as those employed in deep learning, have become a fundamental technology in information processing. These models were originally inspired by biological neural networks in the brain, which achieve robust and highly advanced information processing through the spatiotemporal dynamics arising from a large number of unreliable elements, all while consuming remarkably low amounts of energy. The increasing demand for highly efficient computing technologies highlights the importance of further development of brain-inspired computing.

Given the potential of optical computing and brain-inspired computing, the development of photonic neural networks is considered promising. A number of attempts have already been made to develop photonic neural networks, through which it has become clear that photonic neural networks should not merely be photonic implementations of existing neural network models. Instead, photonic neural networks need to be developed as a fusion of optical computing and brain-inspired computing, where the spatiotemporal aspects of light and the spatiotemporal dynamics of neural networks are expected to play crucial roles.

This book presents an overview of recent advances in photonic neural networks with spatiotemporal dynamics. It particularly focuses on the results obtained in the research project "Computing Technology Based on Spatiotemporal Dynamics of Photonic Neural Networks" (grant number JPMJCR18K2), which is conducted from October 2018 to March 2024 in CREST Research Area "Technology for Computing Revolution for Society 5.0" of Japan Science and Technology Agency (JST).

The computing and implementation paradigms presented here are outcomes of interdisciplinary studies by collaborative researchers from the three fields of nonlinear mathematical science, information photonics, and integrated systems engineering. This book offers novel multidisciplinary viewpoints on photonic neural networks, illustrating recent advances in three types of computing methodologies: fluorescence energy transfer computing, spatial-photonic spin system, and photonic reservoir computing.

The book consists of four parts: The first part introduces the backgrounds of optical computing and neural network dynamics; the second part presents fluorescence energy transfer computing, a novel computing technology based on nanoscale networks of fluorescent particles; the third and fourth parts review the models and implementation of spatial photonic spin systems and photonic reservoir computing, respectively.

These contents can be beneficial to researchers in a broad range of fields, including information science, mathematical science, applied physics, and engineering, to better understand the novel computing concepts of photonic neural networks with spatiotemporal dynamics.

This book would not have been possible without the invaluable contributions of the members of our project. We would like to thank the contributors for writing excellent chapters: Ángel López García-Arias, Yuichi Katori, Takuto Matsumoto, Masaki Nakagawa, Takahiro Nishimura, Yusuke Ogura, Jun Ohta, Kiyotaka Sasagawa, Suguru Shimomura, Ryo Shirai, Sho Shirasaka, Michihisa Takeuchi, Masafumi Tanaka, Naoya Tate, Takashi Tokuda, Hiroshi Yamashita, and Jaehoon Yu. We especially appreciate the considerable assistance from Hiroshi Yamashita in coordinating the manuscripts toward publication. We also thank Ken-ichi Okubo and Naoki Watamura for their contributions in reviewing manuscripts.

We would like to express our gratitude to Prof. Shuichi Sakai, the supervisor of JST CREST Research Area "Technology for Computing Revolution for Society 5.0," for his farsighted advice and encouragement to our project. We would also like to extend our appreciation to the area advisors for their insightful comments: Shigeru Chiba, Shinya Fushimi, Yoshihiko Horio, Michiko Inoue, Toru Shimizu, Shinji Sumimoto, Seiichiro Tani, Yaoko Nakagawa, Naoki Nishi, and Hayato Yamana. We also thank the editorial office of Springer for the opportunity to publish this book.

Osaka, Japan — Hideyuki Suzuki
Osaka, Japan — Jun Tanida
Kyoto, Japan — Masanori Hashimoto
June 2023

Contents