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内 容 简 介

本书为原清华大学光存储国家工程中心主任，国家重点基础研究光存储项目首席科学家徐端颐教授近年来在国外讲学交流使用的讲义。本书系统介绍利用光的振幅、频率(波长)、相位及偏振等物理参量均可携带记录信息的特性，与几何三维空间相结合实现多维光学信息存储的原理和相关技术。本书内容涉及各种光与物质相互作用的微观物理化学效应及多维函数调制编码、光学固态存储器设计等核心技术，可供各有关专业人士参考。

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Foreword

Professor Duanyi Xu was director and founder of Optical Memory National Engineering Research Center (OMNERC) at Tsinghua University, chief scientist of National Basic Research Project and an excellent scientist on optical storage in China. He led and achieved Chinese National Basic Research Planning on "Super-density and Super-speed Optical Memory" etc. national key projects. Professor Xu began to study principles of multidimensional optical storage from 1990s early, and based on medium absorb photon of different frequencies and intensity to carry out the multi-wavelength and multi-level (MW/ML) optical storage, that is earliest result of multidimensional optical storage in this country. Since then, he proposed the theory of photo-induced electron transfer in medium, and employed this principles to study and develop super-resolution MW/ML photochromic optical storage and 3-dimensional MW/ML optical solid state memory cell with more space to present a variety of new principles and techniques for optical storage, to win China National Science and Technology Award that gave OMNERC, Tsinghua University a position of national prominence in multidimensional optical storage.

The multidimensional optical storage is a developing interdisciplinary research field of photonics, photophysics, photochemistry, materials and information science. So the book presents all accomplishments of author's research team with every field experts more 20 years in optical storage and up-to-date literatures in the world that introduces the principles systematically of multidimensional optical storage and engineering implementation, examines the impact to future technologies and challenges, summary and offers a thought-provoking and entertaining vision about "Multidimensional Optical Storage". Meanwhile this book devoted to description of the key building principles, experimental and testing technology for multidimensional optical storage, to perform the first detailed study on the photochemistry materials, binary optical ML lasers/Photodetectors hybrid integration, self-assembled ultrathin films, dual-mode molecular modulator, multidimensional codes and MW/ML CD-ROM duplication technology etc.

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This book is the first provide a framework for thinking about the future Multidimensional Optical Storage, it create a structure for strategic planning and development for exploring potential development road map to the optical memory and should appeal to the readers in universities and industry to understand the fundamental principles of Multidimensional Optical Storage. I am confident it will be an important valuable resource for readers and future specialists who engaged upon information science and technology.

Bingkun Zhou
President of the Chinese Optical Society
Members of the Chinese Academy of Sciences
Professor of Department of Electronic Engineering
at Tsinghua University

Preface

The world is challenged by exploding amounts of data. Around the world, vast quantities of data are generated for video, audio, pictures, documents, newspapers, and other publication from ZB (10^{21} byte) to YB (10^{24} byte), even much more for Internet every day. So far, all of these data are stored with magnetic storage, optical storage, and IC solid state memory successfully by improving storage capacity with minifying recording elements. However, all of these two-dimensional storage methodologies are reaching their physical limit. Therefore, the expansion of storage capacity has to come from the advancement of multi-dimensional storage technology as new direction. Since there is a lot of physical and chemical interaction between light and matter that can be used for information recording, optical storage is more feasible than magnetic storage or IC solid state memory in achieving multi-dimensional storage. The Optical Memory National Engineering Research Center (OMNERC) at Tsinghua University started to research multi-dimensional optical storage in 1991. The research investigated several methods to increase the recording capacity: use multi-wavelength (different frequencies); multi-level (different optical density); different polarization of light (different spatial angle); and different recording element geometry (length, width, and depth). The research projects covering the recording principles, recording medium, and engineering applications are part of the National Key Basic Research Projects and have obtained a series of achievements and patents.

Interest in this field has been growing continuously in recent years. Dhawat E. Pansatiankul and Alexander A. Sawchuk proposed "Multidimensional Modulation Codes and Error Correction for Page-Oriented Optical Data Storage" in 2001; Erez Louidor, Tze Lei Poo, etc. proposed "Maximum Insertion Rate and Capacity of Multi-dimensional Constraints" in 2008; and Min Gu and Xiangping Li proposed "The Road to Multi-Dimensional Bit-by-Bit Optical Data Storage" in 2010. Their papers are undoubtedly important references for studying multi-dimensional optical storage. Since most of our past research works were published in Chinese, some foreign friends frequently request us to introduce our works (patents) in more detail, and if possible, publish them as a book in English.

A preliminary review of the literature shows that numerous related research projects on this field have been carried out, but that there was no systematic study on multi-wavelength and multi-level optical storage yet. My book will let people obtain a comprehensive and balanced picture of this field.

Multi-dimensional storage is based on photonics, photochemistry, photophysics, photochromism and materials science, with the reversible transfer between photon and collective atomic excitation in the medium. This important study will be introduced to general reader in detail with accurate expressions derived by using density matrix equations of motion, coupled wave equations for different frequency photon, photo-nonlinear reaction in medium, stereochemistry and isomerization, preservation of photon energy during storage, margin analysis based on rigorous modeling, conversion efficiency nano-crystalline file, photochromic dye in amorphous state, electron delocalization valence, error correction and application probabilities, the advantages like more performance with less energy consumption and high sensitivity (less noise, higher data rate and more flexible cases), as well as the disadvantages like more temporary nature, incompatibility, and manufacturing problems. In conclusion, photons and light seem to be better than electrons and electric current to carry and store information.

The book is organized as following: Chap. 1 presents an introduction to overview the history of optical digital data storage development and up to date achievements of optical storage in China, as well as the big data storage and application, the frontier science and technologies related to the optical storage and advanced efforts for multi-dimensional optical storage. Chapter 2 presents the mechanism of multi-dimensional optical storage, including the principles of photophysics, photochemistry, photo-induced electron transfer process, and reaction control, as well as other actions of photon with inorganic materials, organometallic polymers, and synthetic photosynthesis. Based on Chap. 2, Chap. 3 continues to discuss the recording process of multi-dimensional optical storage, including photochromic reaction mechanism for multi-dimensional storage, recording model, and quantitative evaluation for absorbable spectrum of medium. Chapter 4 introduces another key part: laser sources and super-resolution technology for multi-dimensional optical storage, such as micro-aperture semiconductor laser and optical injected quantum dot laser etc. Chapter 5 focuses on fundamentals and configurations of multi-wavelength and multi-level (MW/ML) with super-resolution mask storage system, including super-resolution MW/ML disc, optical channel characteristics, modulation and coding, MW/ML error code correction and multi-level run-length limited coding, rewritable multi-level storage, multi-level Blue-ray Disc (BD) drive, multi-level CD-ROM, and duplication technology. Chapter 6 deal with some new mechanism of three-dimensional (3D) multi-level storage: two-photon absorption 3D optical storage, vertical resolution and adaptive aberration correction, multi-channel and multi-layer parallel read/write, 3D MW/ML optical solid state memory, and multi-valued polarization-sensitive storage. Chapters 7 and 8 present principles of the volume holographic storage and multi-wavelength volume holographic storage and devices, including various dynamic static speckle multiplexing, polarized volume holographic storage, and orthogonal polarized dual channel

system based on photochemistry and optically injected quantum dot laser, and advanced polarized volume holographic storage with dithienylethenes and nonintegrated photonic materials. The introduction part of every chapter provides a guide those who may have less knowledge of the field. Each chapter ends with highlights of the content covered in the chapter, as a review of the material. The multi-dimensional optical storage brings out more expandable development space, as a result of a lot of new research achievement on the fundamental theory of the interaction of light with medium to nano-photonics integration process technology and equipment for next-generation optical storage. Meanwhile, various appendixes of mathematical symbols and physical and chemical constants used in this book, and more than 500 related articles are listed in the end of the book as reference for readers.

The book is based on systematic research work, thesis papers, as well as collection of some related research from abroad. The book also discusses the nano-integrated photonic materials and nano-photonics integration process, including principles of optical physics and their affection for data storage, ensuring photons storage, generation, and measurement, broadband waveguide, and margin analysis based on rigorous modeling and preservation process. This book presents both principles and applications to expand the storage space from 2D to 3D or even multi-dimensional with light gray scale (intensity), color (different wavelengths), polarization, and coherence of light, which are used to improve the density, capacity, and data transfer rate of optical data storage. Moreover, the book also discusses the application implementation technologies to make mass data storage devices. Some new high-sensitivity mediums, which have linear absorption characteristics for different wavelength and intensity to light, are introduced too.

Primarily, this book is a textbook on optical engineering for graduate students, which is intended to provide information about the most advanced progress and future development in the field of optical storage. I have successfully used some preliminary versions of selections from this book, such as "Optical super resolution mask 3D storage," "Optical solid state memory based on photochemistry," "Big data multi-dimensional codes," "Theory of nanostructure fabrication for photonics integration devices," in courses at Tsinghua University, and other universities as academic exchange or short course, and also as some subjects of SPIE international conferences. It can be used for training future researchers at both undergraduate and graduate levels, as well as post-education and training program. Most of the materials covered in this book were developed during the teaching of the courses and refined with valuable feedback from these course participants. It is hoped that this book could be used both as a textbook and as a reference for researchers and engineers. Some developing researches, such as photon rate equations, multi-wavelength lasers, highly efficient broadband modulation, vertical resolution, three-dimensional qubit scattering, color free-electron laser, nanoscale nonlinear optical processes, interactions between electrons and photons, excitation dynamic devices, microcavity-based devices, combination of photonic crystals and plasmonics to various linear, nonlinear optical functions, and light-activated nanoparticles medium, have been mentioned as references. The book is also valuable for

industries and business: It provides a critical evaluation of the current status of multi-dimensional optical storage technologies, materials, nano-photonic devices manufacturing, and testing equipment. The book also introduces diversified novel multi-dimensional optical storage principles, various laser sources, organic/inorganic materials, and particular experimental results.

Considering different levels of readers, the book introduces concepts with minimal mathematical details, and examples are provided to illustrate principles and applications. It can enable a newcomer to this field to acquire the necessary background knowledge to undertake research and development of advanced optical storage. In addition, I hope this book to be helpful to promote recent optical memory development and make them accessible to engineers in this field. At several places in the text, tables are provided to facilitate conversion to other units. The book attempts to present the topic of each chapter as self-contained unit and to provide up-to-date research evidence to the greatest extent possible. So this book highlights and illustrates the background and the current status of multi-dimensional optical storage and systematically describes many aspects of the MW/ML optical storage, from the basic principles to engineering applications. It can be references to researchers, engineers, and graduate and undergraduate students in related field.

Using conventional optical manufacturing equipment with precision injection duplication, OMNERC at Tsinghua University created multi-dimensional optical storage devices like the multi-wavelength and multi-level disc and photochemistry optical solid state memory cell which was built on the silicon process with optical interconnections. It simplified the process to make an all-optical memory and made it easier to commercialize and integrate it into application-specified devices, which had optical correlators for detecting signals. A new generation of hybrid nano-materials, which involved different levels of integration of organic and inorganic structures, holds considerable new fundamental science and novel technologies to prepare inorganic nanostructures for multi-dimensional optical storage. Those new materials were developed by our main partner Physics Chemistry Institute of CAS in China, which made it flexible to fabricate components with diverse functions and heterogeneous characteristics. Novel easy synthetic technique and processing of nano-materials, such as new types of molecular nanostructures and supramolecular assemblies with varied nano-architectures, and self-assembled periodicity to induce multi-functionality and cooperative effects were developed for applications. These accomplishments made favorable condition to research on multi-dimensional optical storage. So this book is the result of all researchers in OMNERC and in Physics Chemistry Institute of CAS, as well as other collaboration experts. I would like to express my sincere thanks to these experts, professors, graduate students, and my colleagues. In addition, I would express my sincere appreciation to Prof. Bingkun Zhou and the editors of Springer Press and Tsinghua University Press. This book could not be accomplished and published successfully without their strong support and help.

November 2015 Duanyi Xu

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