

Hans J. Coufal Demetri Psaltis
Glenn T. Sincerbox (Eds.)

Holographic Data Storage

With a Foreword
by Alstair M. Glass and Mark J. Cardillo

With 228 Figures, 64 in Color and 12 Tables



Springer

Dr. Hans J. Coufal
IBM Corporation
Almaden Research Center
San Jose, CA 95120-6099, USA
E-mail: coufal@almaden.ibm.com

Professor Demetri Psaltis
California Institute of Technology
Department of Electrical Engineering
Pasadena, CA 91125, USA
E-mail: psaltis@caltech.edu

Professor Glenn T. Sincerbox
University of Arizona
Optical Sciences Center
Tucson, AZ 85721, USA
E-mail: sinbox@u.arizona.edu

Library of Congress Cataloging-in-Publication Data

Holographic data storage / H.J. Coufal, D. Psaltis, G. Sincerbox (Eds.)
p. cm. -- (Springer series in optical sciences, ISSN 0342-4111 ; 76)
Includes bibliographical references and index.
ISBN 3540666915
1. Optical storage devices. 2. Holography. 3. Computer storage devices. 4. Optical data processing. I. Coufal, H. II. Psaltis, Demetri. III. Sincerbox, Glenn T., 1937-. IV. Springer series in optical sciences ; v. 76.

TA1635 .H65 2000
621.39'767--dc21

00-023971

ISSN 0342-4111

ISBN 3-540-66691-5 Springer-Verlag Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer-Verlag. Violations are liable for prosecution under the German Copyright Law.

Springer-Verlag Berlin Heidelberg New York
a member of BertelsmannSpringer Science+Business Media GmbH

© Springer-Verlag Berlin Heidelberg 2000
Printed in Germany

The use of general descriptive names, registered names, trademarks, 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.

Data conversion by EDV-Beratung F. Herweg, Hirschberg
Cover concept by eStudio Calamar Steinen using a background picture from The Optics Project. Courtesy of John T. Foley, Professor, Department of Physics and Astronomy, Mississippi State University, USA
Cover production: *design & production* GmbH, Heidelberg

Printed on acid-free paper SPIN 10688525 56/3141/di 5 4 3 2 1 0

Contents

List of Contributors	XXI
----------------------------	-----

Part I Introduction

History and Physical Principles

G.T. Sincerbox	3
1 Holographic Storage Principles	4
1.1 Redundant Storage	6
1.2 Multiplexing	7
1.3 High Data Rate	9
1.4 Rapid Access	9
1.5 Novel Functions	9
2 Historical Development	10
2.1 Bell Labs and the Digital Page	11
2.2 IBM HOSP	11
2.3 RCA Holographic Memory	12
2.4 3M Holographic Data Storage System	12
2.5 Thompson-CSF Read-Write Memory Using Angular Multiplexing	13
2.6 NEC Holographic Coding Plate or Holotablet	13
2.7 Harris-Intertype Wide-Band Recorder	13
2.8 Hitachi Holographic Video Disk	14
2.9 Optical Data Systems Holoscan	14
2.10 Holographic Storage in the Soviet Union	14
2.11 NEC Holographic Disk	15
2.12 MEI Kanji Character Generation System	15
2.13 Tamarack Multistore	16
2.14 The PRISM Test Stand	16
2.15 Stanford University	16
2.16 Holoplex Memory Device for Fingerprint Verification	17
2.17 Rockwell Read-Only Demonstrator	17
2.18 IBM DEMON	18
3 Summary	18
References	19

Volume Holographic Multiplexing Methods	
G. Barbastathis and D. Psaltis	21
1 Holographic Storage and Retrieval	21
1.1 Overview of Holographic Multiplexing Methods	25
1.2 Holographic Storage Geometries and Imaging Systems	28
2 Scattering from Volume Gratings	30
2.1 Volume Diffraction in the Born Approximation	31
2.2 Volume Diffraction of Scalar Fields	33
2.3 Volume Diffraction Calculations Using the k -Sphere Formulation	42
2.4 Visualization of the Multiplexing Methods on the Grating Space	47
2.5 Grating Manifold Motion and Fractal Multiplexing	52
3 Architectures for Holographic Memories	55
3.1 The Holographic 3-D Disk Geometry	55
3.2 The Holographic Random-Access Memory (HRAM)	57
3.3 The Phase Conjugate Geometry	57
4 Summary	59
References	59

Fundamental Noise Sources in Volume Holographic Storage	
C. Gu, P. Yeh, X. Yi, and J. Hong	63
1 Cross-Talk Noise	63
1.1 Theoretical Formulation	64
1.2 Cross-Talk Noise and Signal-to-Noise Ratio	66
1.3 Storage Capacity	72
2 Intrinsic Scattering Noise	76
3 Noise Gratings	79
4 Conclusion	87
References	87

Part II Recording Media

Bit Error Rate for Holographic Data Storage	
J.A. Hoffnagle and C.M. Jefferson	91
1 Definition of Bit Error Rate	92
2 BER in Terms of Pixel Distribution Functions	93
3 Experimental Distributions of CCD Pixel Values	94
4 Applications	99
References	100

Media Requirements for Digital Holographic Data Storage

R.M. Shelby	101
1 Ideal Media Parameters	101
1.1 Optical Quality	101
1.2 Sensitivity	103
1.3 Dynamic Range	104
1.4 Absorption	105
1.5 Volatility	105
2 Example Materials	105
3 Stability of Stored Data	107
3.1 Dark Decay	107
3.2 Decay During Readout: Fixing	107
3.3 Two-Color Recording	108
4 Hologram Fidelity and Bit Error Rate	108
5 Conclusions	109
References	109

Inorganic Photorefractive Materials

K. Buse and E. Krätzig	113
1 Charge Transport	114
2 Storage Properties: Dark Storage Time, Response Time, Capacity, Sensitivity	117
3 Theoretical Performance Limits	118
4 Various Crystals	119
5 Nondestructive Readout	121
6 Conclusions	122
References	123

Hologram Fixing and Nonvolatile Storage**in Photorefractive Materials**

S.S. Orlov and W. Phillips	127
1 Thermally Assisted Ionic Fixing	128
1.1 Hologram Fixing and Ionic Conduction in LiNbO ₃	130
1.2 Lifetime of Fixed Ionic Gratings	131
1.3 High-Low Fixing	134
2 Fixing by Spontaneous Polarization Modulation	136
3 Two-Photon Holographic Recording in Stoichiometric Lithium Niobate	138
3.1 Undoped Stoichiometric Lithium Niobate	139
3.2 Doped Stoichiometric Lithium Niobate	144
3.3 Summary on Two-Photon Recording in LiNbO ₃	146
References	146

Two-Color Holography in Lithium Niobate

R. Macfarlane, H. Guenther, Y. Furukawa, and L. Kitamura	149
1 Materials	151
2 Experimental	152
3 Spectroscopy and Sensitization	152
4 Photorefractive Properties	153
4.1 Sensitivity	154
4.2 Gating Ratio	155
4.3 Dynamic Range	155
4.4 Dark Decay	156
4.5 The Role of Iron	156
5 Conclusion	157
References	158

Overview of Photorefractive Polymers**for Holographic Data Storage**

B. Kippelen	159
1 Brief History of Photorefractive Polymers	159
2 Physics and Chemistry of Photorefractive Polymers	161
2.1 Photogeneration	161
2.2 Transport	161
2.3 Index Change: Electro-Optic and Orientational Effects	163
3 Performance of Current Photorefractive Polymers	164
3.1 Spectral Sensitivity	164
3.2 Dynamic Range	164
3.3 Material Stability	166
3.4 Speed	166
3.5 Applications	167
4 Trends and Outlook	167
References	168

Photopolymer Systems

R.T. Ingwall and D. Waldman	171
1 Introduction	171
2 Chemistry of Photopolymer Systems	171
2.1 Monomers	171
2.2 Photoinitiation Systems	173
2.3 Binders	174
3 Recording Characteristics of Photopolymers	175
4 Recording Mechanism	177
4.1 Refractive Index Changes	177
4.2 Component Segregation	180

5	Recording Thick Photopolymer Holograms	181
5.1	Light Absorption	181
5.2	Low Viscosity	184
6	Image Quality in Photopolymer Holograms	185
6.1	Shrinkage	185
7	Data Storage in Photopolymer Holograms	191
7.1	Multiplexing	191
7.2	Data Page Recording	194
8	Summary	195
	References	195

Photopolymers for Digital Holographic Data Storage

L. Dhar, M.G. Schnoes, H.E. Katz, A. Hale, M.L. Schilling,
and A.L. Harris

1	Hologram Formation in Photopolymer Systems	200
2	Photopolymer Materials	200
3	Formation of Thick, Optically Flat Media	201
4	Holographic Characterization of Photopolymer Media	202
4.1	Recording-Induced Bragg Detuning	202
4.2	Dynamic Range	203
5	Holographic Digital Data Storage in Photopolymer Media	205
6	Summary	207
	References	207

Photoaddressable Polymers

T.	Bieringer	209
1	Photoaddressable Polymers	209
1.1	Photochemistry of Azobenzene	210
1.2	Azobenzene Containing Polymers	211
1.3	Liquid Crystalline Side Chain Polymers	212
2	Materials Under Investigation	216
2.1	The Choice of the Main Chain	216
2.2	The Spacer	217
2.3	The Choice of the Azo Group	217
2.4	The Choice of the Mesogenic Group	218
2.5	The Azo Group Concentration	218
3	State of the Art in the Literature	219
4	Photoaddressable Polymers from Bayer	221
5	Photoaddressable Polymers Used in Holographic Data Storage	222
6	Open Questions and Outlook	223
	References	223

Part III Components

Laser Sources

B. Pezeshki and S.S. Orlov	231
1 Laser Requirements	231
2 Diode-Pumped Solid-State Lasers	232
3 Semiconductor Lasers	234
References	239

**Beam Deflectors and Spatial Light Modulators
for Holographic Storage Application**

G. Zhou, F. Mok, and D. Psaltis	241
1 Description of the Holographic Disk System	241
2 Recording Density	244
3 SLM Characteristics and System SNR	246
4 Recording Rate	250
5 Beam Deflector for Holographic Data Readout	253
References	256

**Beam Conditioning Techniques
for Holographic Recording Systems**

R.K. Kostuk, M.P. Bernal Artajona, and Q. Gao	259
1 Defocusing	260
2 Random Phase Masks	261
3 Pseudo-Random Phase Masks	263
4 Axiicons	265
5 Discussion and Summary	268
References	268

Detector Arrays for Digital Holographic Storage Applications

S. Campbell and E.R. Fossum	271
1 General Considerations for Detector Arrays	272
1.1 Size, Power and Cost	272
1.2 Number of Pixels, Readout Rate, and Pixel Size Considerations	273
1.3 Noise, Dynamic Range, and Analog-to-Digital Converter Resolution	273
2 Detector Array Choices	274
2.1 Quantum Efficiency	276
2.2 Noise	276
3 Readout Rate	278

4 System Implementation	278
5 Conclusion	279
References	279

Part IV Channels

Modulation Codes for Holographic Recording

B. Marcus	283
1 Block Codes	283
1.1 Correlation Detection and Balanced Block Codes	284
1.2 Sparse Block Codes	285
1.3 Parity Thresholding	286
2 Strip Codes	286
2.1 Balanced and Pseudo-Balanced Strip Codes	287
2.2 Inter-Pixel Interference and Low-Pass Codes	288
2.3 Combined Constant-Weight Low-Pass Codes	289
References	291

Interleaving and Error Correction for Holographic Storage

M.A. Neifeld and W.-C. Chou	293
1 Capacity	294
2 Error Correction	297
3 Interleaving	300
4 Conclusions	305
References	305

Equalization for Volume Holographic Data Storage Systems

B. V. K. Vijaya Kumar, V. Vadde, and M. Keskinoz	309
1 Channel Modeling	310
2 Equalization Methods	311
2.1 Zero Forcing Equalization	312
2.2 LMMSE Equalization	313
2.3 Partial Response (PR) Equalization	314
3 Equalization Results	315
4 Implementation Issues	316
5 Summary	316
References	317

Gray-Scale Data Pages for Digital Holographic Data Storage

G.W. Burr and M.A. Neifeld	319
1 Motivation for Gray-Scale	319
2 Predistortion	321
3 Encoding Digital Data into Gray-Scale Pixels	323

XVI Contents

4	Capacity Estimation	324
5	Optimizing the Error-Correction Coding to Obtain User Capacity	326
6	Summary	327
	References	328

Part V Demonstration Platforms

System Optimization for Holographic Data Storage Systems

G.W. Burr and M.P. Bernal Artajona	331	
1	Noise	331
2	Camera Quantization	334
3	Choice of Fill-Factors and Apertures	335
4	Capacity-Estimation Procedure	337
5	Choice of ECC Design Point: Effect of Variations in Diffraction Efficiency	338
6	Summary	340
	References	340

Tamarack Optical Head Holographic Storage

S. Redfield	343	
1	Roots	343
2	Design Evolution	343
3	Final System Approach	346
3.1	Requirements	347
3.2	Optical Head	347
3.3	Media Disk	348
3.4	Data Format	349
4	Holographic Optical Head	349
4.1	Reference Path Optical Design	349
4.2	Object Path Optical Design	352
5	Mechanical Design	353
5.1	Page Motor Design	353
5.2	HOH-Media Positioning	353
5.3	Changer	354
6	Summary	356

**High-Density, High-Performance Data Storage
via Volume Holography:**

The Lucent Technologies Hardware Platform

K. Curtis, W.L. Wilson, M.C. Tackitt, A.J. Hill, and S. Campbell	359	
1	Materials	360
2	Multiplexing Methods	361
3	Components	363

4	Holographic Demonstration System	365
5	System Evolution	367
6	Summary	367
	References	368
IBM Holographic Digital Data Storage Test Platforms		
	C.M. Jefferson, G.W. Burr, and J.A. Hoffnagle	369
1	PRISM Photorefractive Materials Tester	369
2	DEMON I Holographic Data Storage Engine	374
3	DEMON II Advanced Holographic Digital Data Storage Engine	376
4	Innovative Optics	378
4.1	Axicons	378
4.2	Aspherical Apodizer	379
	References	381
Digital Holographic Demonstration Systems		
by Stanford University and Siros Technologies		
	L. Hesselink	383
1	Optical Architectures	384
2	Capacity Versus Transfer Rate Tradeoff	384
3	Demonstration Platforms	386
4	The Stanford University all Digital System Demonstration (Science, 1994)	386
5	The Siros First Fully Automated Video Demonstration (1995)	391
6	The Siros Fully Automated System with Electronic Readout at Video Rates (PRISM, 1996)	392
7	The Stanford University and Siros Fully Electronic Data Readout System Achieving 1 Gbit/s (HDSS, 2000)	393
8	The Stanford University and Siros 100-Gbytes Capacity and 1 Gbit/s Readout System Demonstrator	395
	References	396
Holographic Read-Only Memory		
	F. Mok, G. Zhou, and D. Psaltis	399
1	Specifications	400
2	Recorder	400
3	Reader	402
4	Replication	404
Digital Holographic Data Storage with Fast Access		
	J. Ma, T. Chang, S. Choi, and J. Hong	409
1	Introduction	409
2	System Architecture	410

XVIII Contents

3 System Operation	412
References	417
A Demonstration Platform for Phase-Coded Multiplexing	
C. Denz, K.-O. Müller, F. Visinka, and T. Tschudi	419
1 Phase-Coded Multiplexing	419
1.1 Phase Code Generation	420
1.2 Arithmetic Image Operations	421
2 Design and Implementation of the Demonstrator	421
3 Experimental Results	423
3.1 Arithmetic Image Operations	425
3.2 Data Encryption	426
4 Summary	427
References	428
Volume Holographic Optical Correlators	
P.A. Mitkas and G.W. Burr	429
1 Optical Correlation	429
2 Volume Holographic Correlators	431
3 Volume Holographic Database System Architecture	432
3.1 Associative Recall with Binary Data	433
3.2 Associative Recall with Image Data	434
4 Fuzzy Volume Holographic Search Engine	435
4.1 All-Optical Search-and-Retrieve Demonstration	436
5 Evaluation of Associative Recall	437
6 Conclusions	443
References	443
<hr/> Part VI Competing Technologies <hr/>	
The Continuing Evolution of Magnetic Hard Disk Drives	
E. Grochowski	447
1 Areal Density	448
2 Magnetic Recording Head Physics GMR	450
3 Magnetic Disk Design and Physical Spacing	452
4 The Mechanical HDD Design and Form Factor Evolution	453
5 Price	455
6 Performance and Coding	457
7 Super Paramagnetism and “Limits” for Magnetic Recording	459
8 Conclusion	462
References	462

Optical Disk Storage Roadmap	
B.H. Schechtman	463
1 Product Categories	464
2 Technology Status and Outlook	467
3 Summary.....	472
References	472
 Alternative Storage Techniques	
G.R. Ashton and W.C. Mitchell.....	475
1 Three-Dimensional Optical Recording	475
1.1 Electron Trapping Optical Memory	475
1.2 Liquid Crystal Optical Disk	475
1.3 Surface-Enhanced Raman Optical Data Storage	476
1.4 Optical Tape Technology	476
2 New Storage Forms	477
2.1 Persistent Spectral Hole Burning	477
2.2 Two-Photon Three-Dimensional Recording	477
2.3 Charged Particle Beam Technology	477
2.4 Optical Storage Card	478
2.5 Scanning Probe Storage	478
3 Conclusions.....	479
References	479
 Index	481