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Winter College on Optics and Photonics
7 - 25 February 2000

1218-3

"Holographic Optical Storage Principles & Materials"

G. SINCERBOX
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USA

HOLOGRAPHIC OPTICAL STORAGE PRINCIPLES AND MATERIALS

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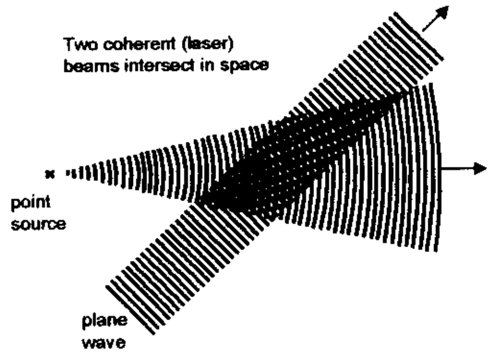
Outline

- concepts of holographic storage
- features
- multiplexing
- new news
- system requirements
- material requirements
- photorefractives; data volatility
- solutions to data volatility
- materials testing
- bit-error rate
- applications
- costs
- issues
- summary

THE PHYSICS OF HOLOGRAPHY: INTERFERENCE



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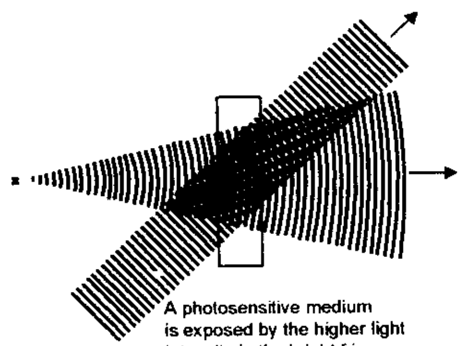
THE PHYSICS OF HOLOGRAPHY: RECORDING



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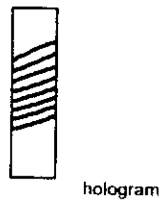
THE PHYSICS OF HOLOGRAPHY: MECHANISMS

The photosensitive medium replicates the fringes as a change in:

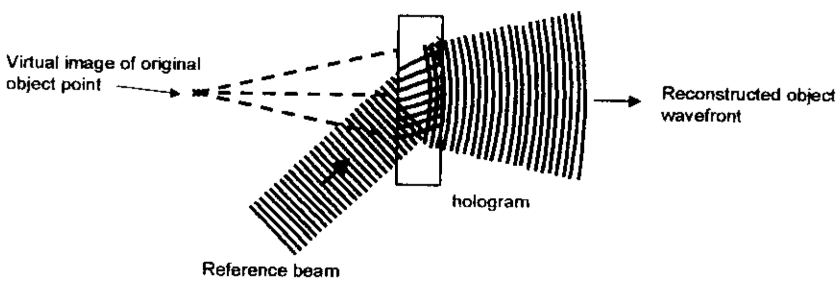
- ➩ absorption
- ➩ refractive index
- ➩ thickness
- ➩ combination



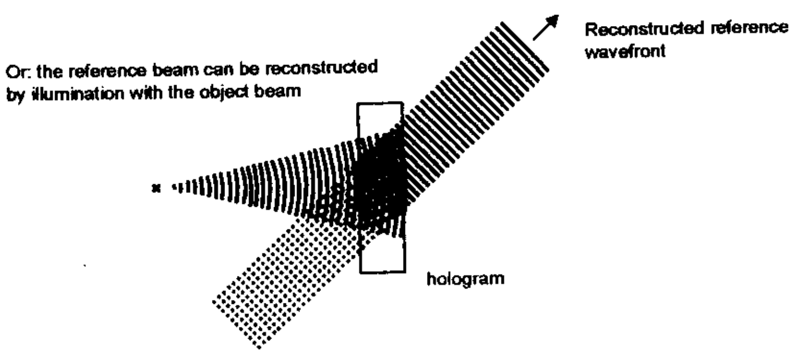
Processing may or may not be required

THE PHYSICS OF HOLOGRAPHY: RECONSTRUCTION OF THE OBJECT BEAM

Light from one beam is diffracted by the structure to exactly replicate the other beam



THE PHYSICS OF HOLOGRAPHY: RECONSTRUCTION OF THE REFERENCE BEAM



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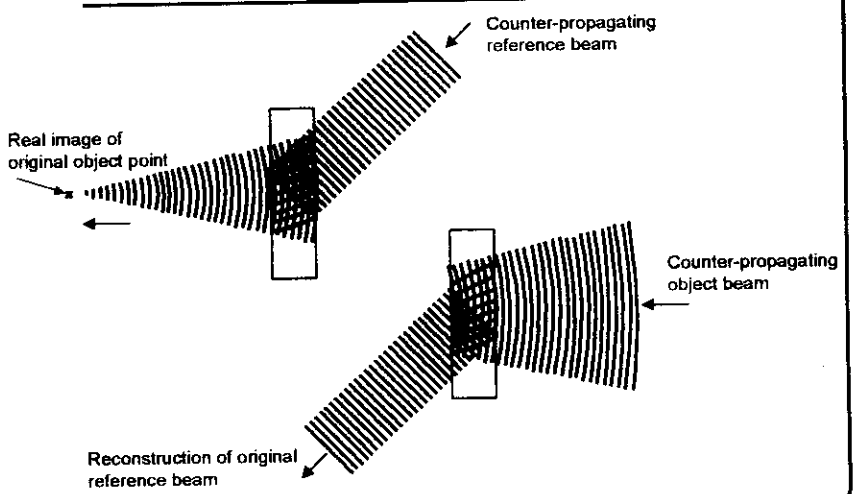
THE PHYSICS OF HOLOGRAPHY: CONJUGATE ILLUMINATION



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FUNDAMENTALS OF HOLOGRAPHY - Recording

- Object wavefront: $\widetilde{A}_o = A_o(x,y)e^{i\Phi_o(x,y)}$
- Reference wavefront: $\widetilde{A}_r = A_r(x,y)e^{i\Phi_r(x,y)}$
- Interference: $A_o(x,y)e^{i\Phi_o(x,y)} + A_r(x,y)e^{i\Phi_r(x,y)}$
- Recording medium responds to intensity:

$$I(x,y) = \left(A_o(x,y)e^{i\Phi_o(x,y)} + A_r(x,y)e^{i\Phi_r(x,y)} \right)\left(A_o^*(x,y)e^{-i\Phi_o(x,y)} + A_r^*(x,y)e^{-i\Phi_r(x,y)}\right)$$

$$= I_o + I_r + A_oA_r^*e^{i(\Phi_o - \Phi_r)} + A_o^*A_re^{i(\Phi_r - \Phi_o)}$$

$$= I_o + I_r + \widetilde{A}_o\widetilde{A}_r^* + \widetilde{A}_o^*\widetilde{A}_r$$

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FUNDAMENTALS OF HOLOGRAPHY- Playback

- Transmission of exposed medium proportional to exposure:

$$t(x,y) = \beta\, E(x,y) = \beta\, I(x,y)t = \beta'\, I(x,y)$$

$$\boxed{t(x,y) = t_b + \beta'\,\widetilde{A}_o\widetilde{A}_r^* + \beta'\,\widetilde{A}_r\widetilde{A}_o^*} \quad = \text{Hologram}$$

- Illuminate hologram with arbitrary wavefront:

$$\widetilde{B} = B(x,y)e^{i\Phi_B(x,y)}$$

- Transmitted wavefronts are:

$$\widetilde{T}(x,y) = \widetilde{B}(x,y)t(x,y) = t_b\widetilde{B} + \beta\,\widetilde{A}_o\widetilde{A}_r^*\widetilde{B} + \beta\,\widetilde{A}_o^*\widetilde{A}_r\widetilde{B}$$

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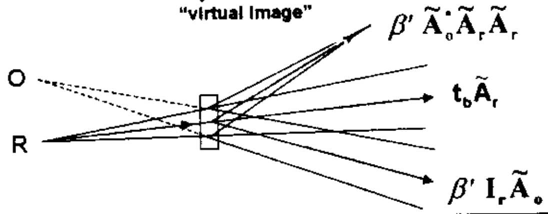
FUNDAMENTALS OF HOLOGRAPHY- Special cases

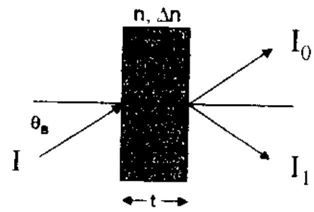
When: $\widetilde{\mathbf{B}} = \widetilde{\mathbf{A}}_r$ (Illuminate with the reference beam)

Then: $\widetilde{\mathbf{T}}(x,y) = t_b \widetilde{\mathbf{A}}_r + \beta' \, \mathbf{I}_r \widetilde{\mathbf{A}}_o + \beta' \, \widetilde{\mathbf{A}}_o^* \widetilde{\mathbf{A}}_r \widetilde{\mathbf{A}}_r$

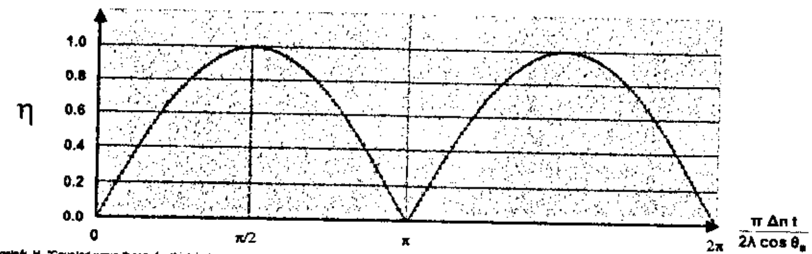
- $t_b \widetilde{\mathbf{A}}_r$: Reference beam modulated by background exposure
- β': Constant
- $\mathbf{I}_r \widetilde{\mathbf{A}}_o$: **reconstructed object beam "virtual image"**
- $\widetilde{\mathbf{A}}_o^* \widetilde{\mathbf{A}}_r \widetilde{\mathbf{A}}_r$: Object wavefront focusing to a real image at twice the angle



COUPLED WAVES



$$\eta = \frac{I_1}{I} = \sin^2\left(\frac{\pi \Delta n t}{2\lambda \cos\theta_B}\right)$$



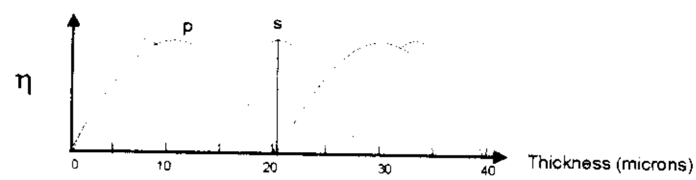
Kogelnik, H. "Coupled wave theory for thick hologram gratings," Bell System Tech. J., 48 (9), 2909, 1969

POLARIZATION EFFECTS

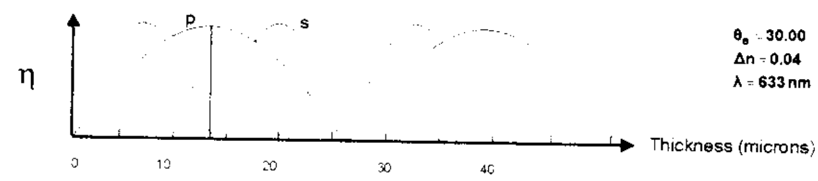
$$\eta = \frac{I_1}{I} = \sin^2\left(\frac{(\hat{p}\bullet\hat{q})\pi \Delta n t}{2\lambda \cos\theta_B}\right)$$

$$(\hat{p}\bullet\hat{q})_p = \cos 2\theta_B$$

$$(\hat{p}\bullet\hat{q})_s = 1$$



$\theta_B = 24.09$
$\Delta n = 0.04$
$\lambda = 633$ nm



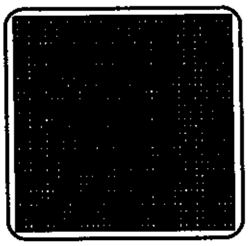
$\theta_B = 30.00$
$\Delta n = 0.04$
$\lambda = 633$ nm

Any complex 3-D object can be treated as an assembly of points, each interfering with the reference beam and with each other

THE DIFFERENCE

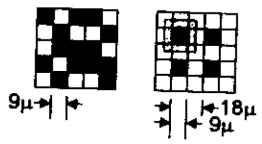
Display & security-emblem holography records an image of the scene or object

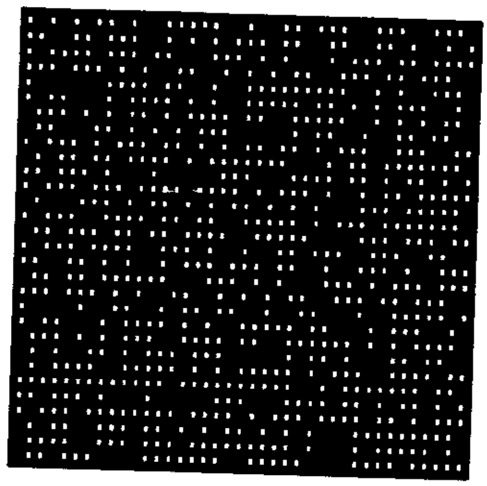
Holographic storage records a digital representation of the scene, object or data



THE INPUT

64 x 64 = 4K
128 x 128 = 16K
256 x 256 = 64K
512 x 512 = 256K
1024 x 1024 = 1M





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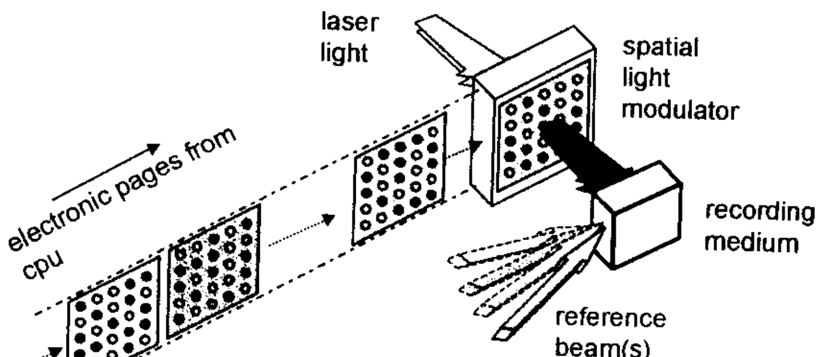
HOLOGRAPHIC STORAGE - RECORDING DATA



record one page at a time, each with a different reference beam

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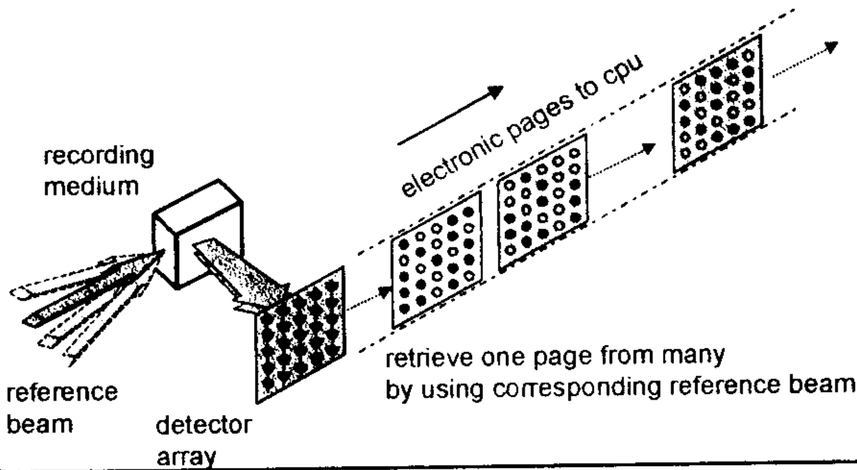
HOLOGRAPHIC STORAGE - RETRIEVING DATA



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FEATURES

- Redundant (distributed) storage
  - less sensitive to local defects
- Page (block) oriented
  - parallel data transfer
  - no data tracking
- Volume storage
  - increased capacity by multiplexing
- Beam addressable
  - random access - low latency
- Novel function

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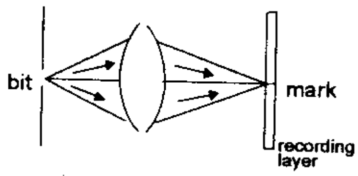
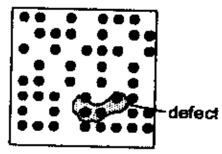
REDUNDANT STORAGE

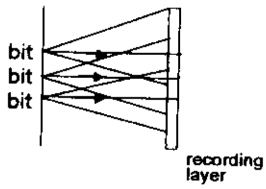
Localized data

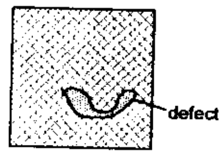




loss of data

Nonlocalized data





loss of SNR

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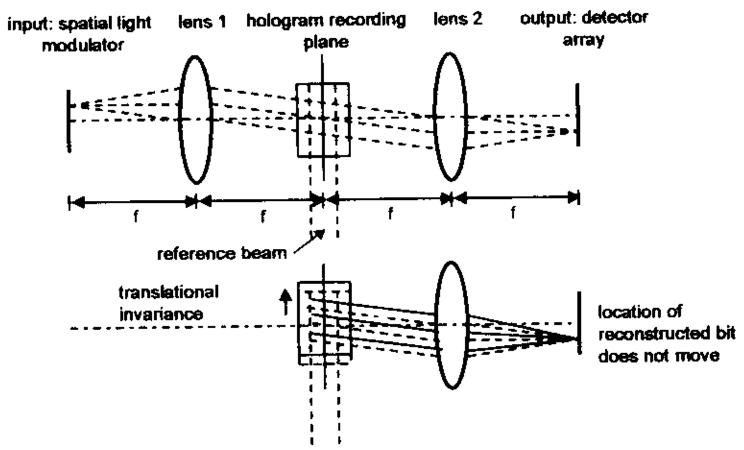
FOURIER TRANSFORM HOLOGRAPHY



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MULTIPLEXING - THE KEY TO CAPACITY

Utilize the entire recording volume, not just the surface
- **each "image" occupies a portion of the entire recording range**
- **create unique, intermixed 3-D structures**
- **not to be confused with multilayer storage**

Utilize some attribute(s) of a light beam that can be independently controlled
- **direction**
- **wavelength**
- **phase**
- **polarization**

Multiplexing can also be used to improve access time

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MULTIPLEXING TECHNIQUES

Angle:	van Heerden, 1963
Wavelength:	van Heerden, 1963
Random phase:	LaMacchia, et. al., 1968
Rotation:	Staebler, et. al., 1975
Deterministic phase:	Denz, et. al., 1991
Peristrophic:	Curtis, et. al., 1994
Shift:	Psaltis, et. al., 1995

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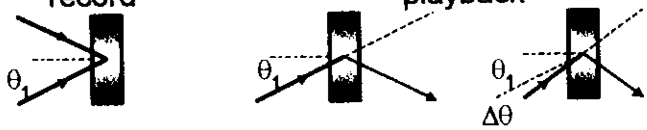
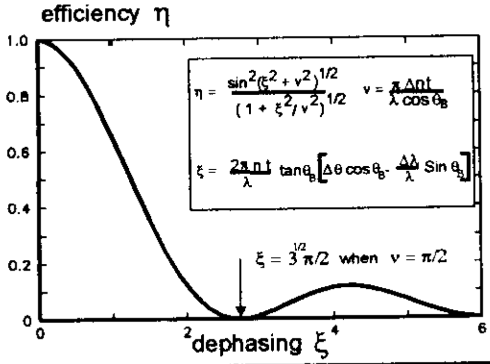
BRAGG EFFECT





thickness (microns)	angle (deg)	wavelength (nm)
100	0.25	9.5
500	0.05	1.9
1000	0.025	0.95
5000	0.005	0.19

$LiNbO_3$:
$n = 2.27$
$\lambda = 500$ nm
$\theta_{air} = 30$

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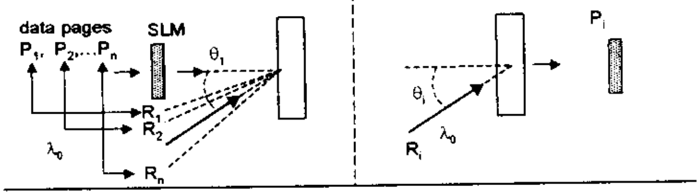
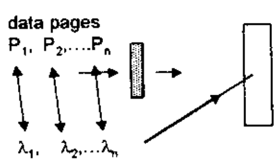
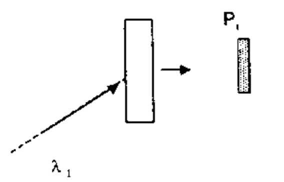
MULTIPLEXING: TWO SIMPLE EXAMPLES

Angle: record each data page with a different reference beam angle



Wavelength: record each data page with a different wavelength





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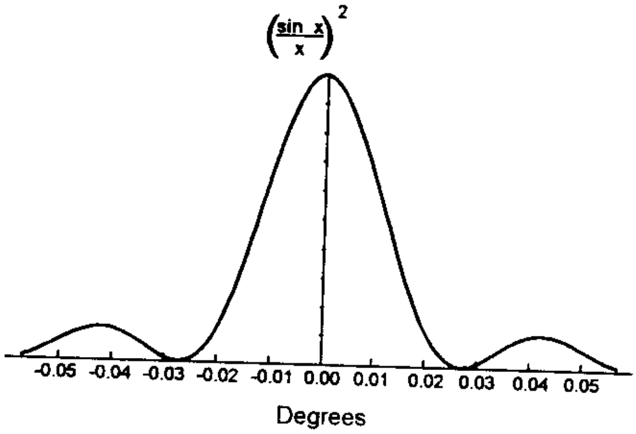
ANGULAR SENSITIVITY



for 1 mm thick $LiNbO_3$ at 500 nm; n = 2.27; θ_{ar} = 30 deg

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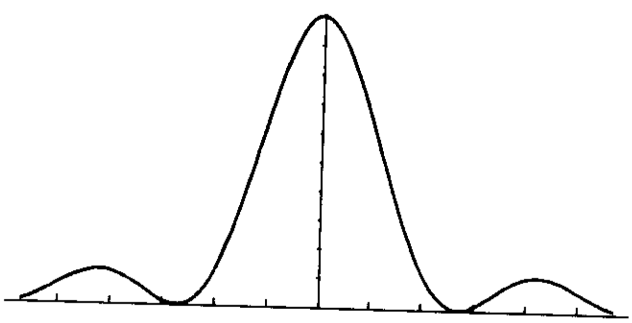

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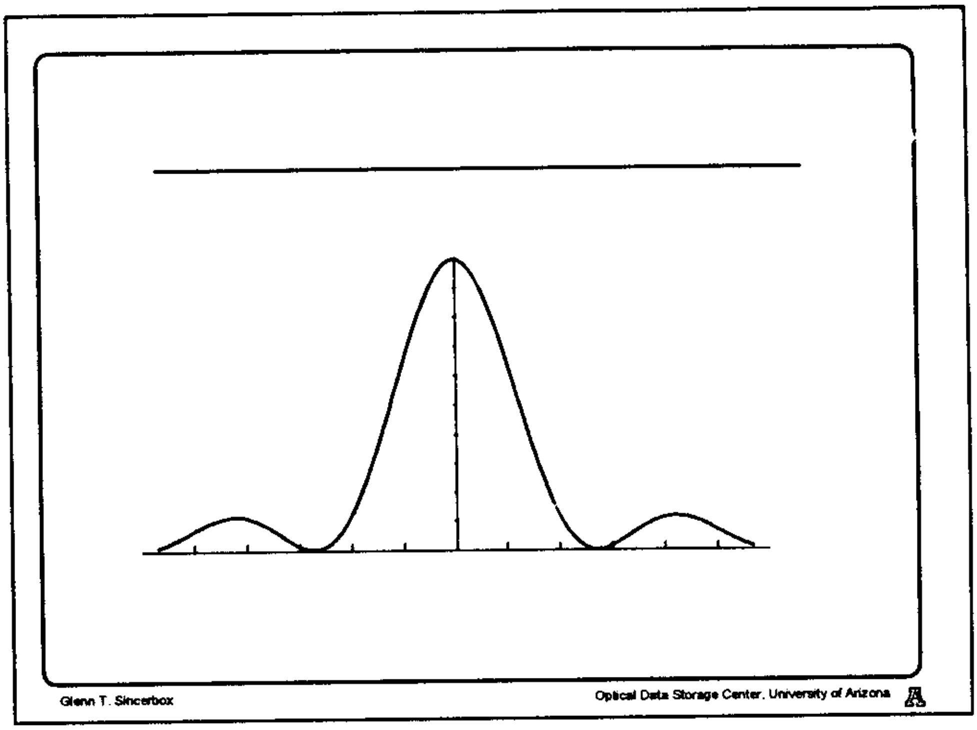
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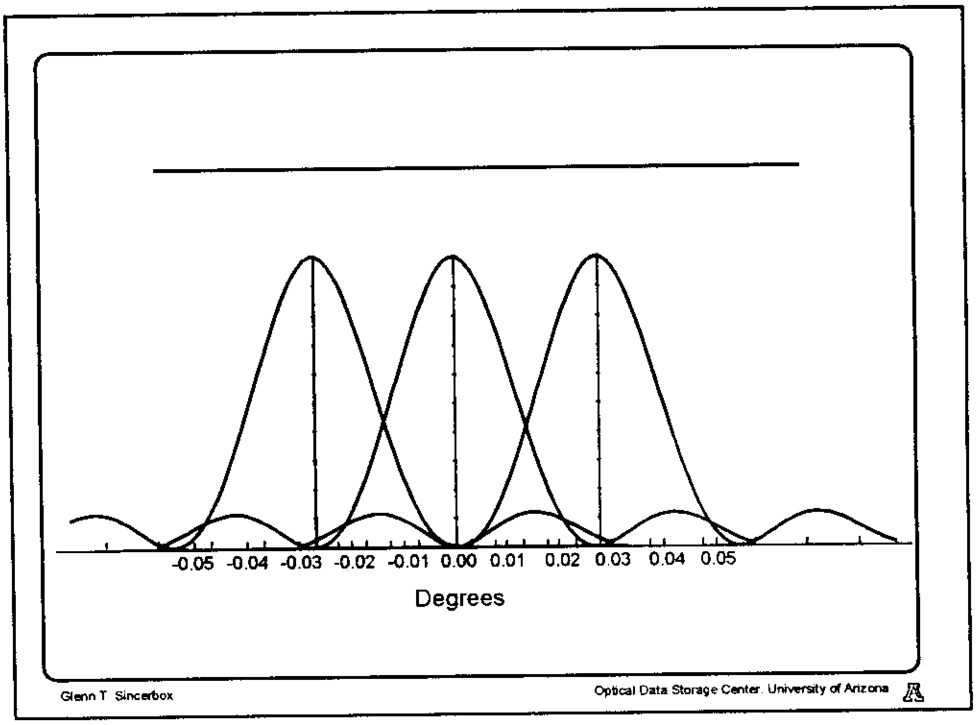
-0.05 -0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02 0.03 0.04 0.05
Degrees
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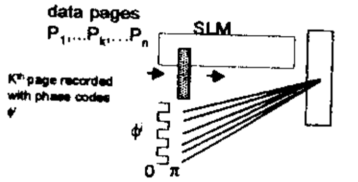
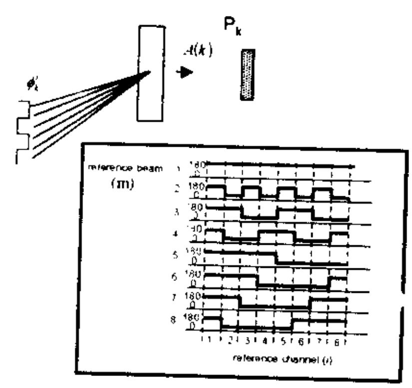
MULTIPLEXING WITH PHASE-ENCODED REFERENCE BEAMS

Use all reference beam angles simultaneously with 0° or π° phase encoding





$$A(k) = \frac{1}{N}\sum_{m=1}^{N}\sum_{i=1}^{N} e^{j\phi_k^i} e^{j\phi_m^i} = 1 \quad for \quad m = k$$

$$= 0 \quad for \quad m \neq k$$

C. Denz, G. Pauliat & G. Roosen, Opt. Com., 85, 171 (1991)

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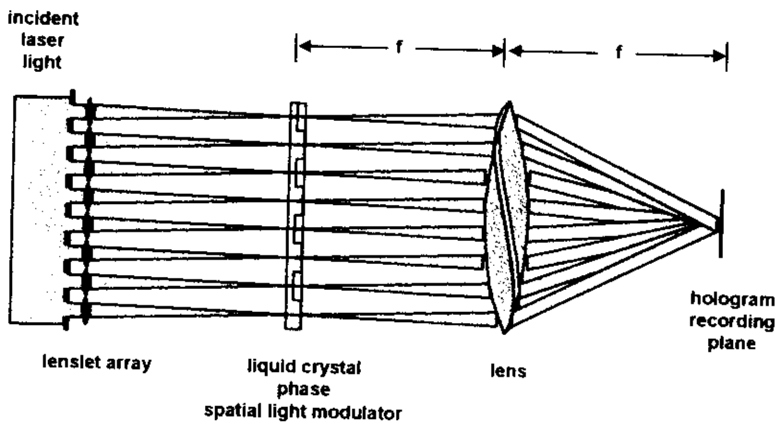
PHASE ENCODING OPTICS - ONE POSSIBILITY -



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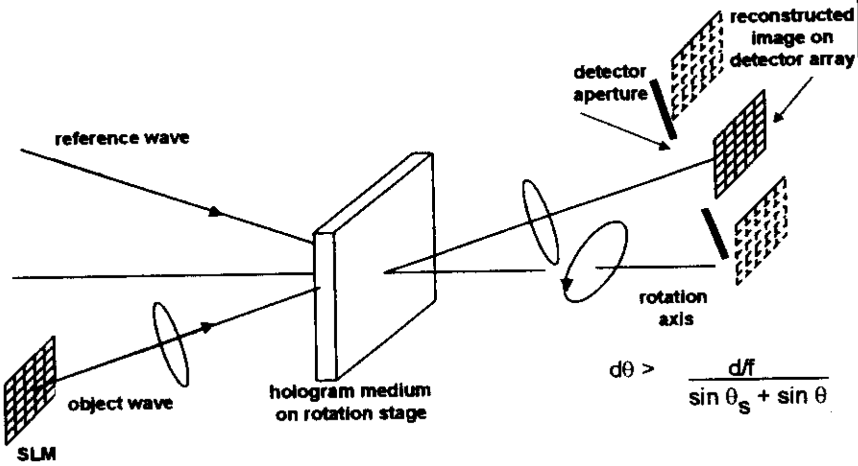
PERISTROPHIC (ROTATION) MULTIPLEXING



$$d\theta > \frac{d/f}{\sin\theta_s + \sin\theta}$$

Curtis, Pu and Psaltis, Opt. Lett., 19, #13, p993 (1994)

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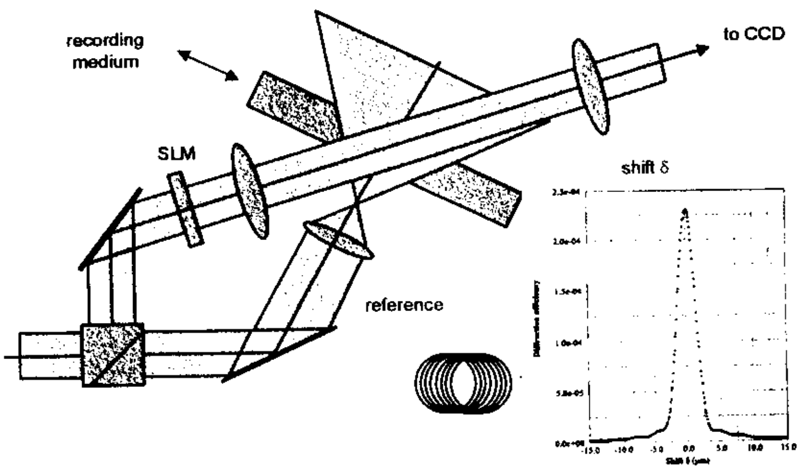
SHIFT MULTIPLEXING



Barbastathis, Levene, Psaltis, Appl. Opt., 35, #14, p2403-2417 (1996)

Fig. 4 Experimental selectivity curve diffraction efficiency η

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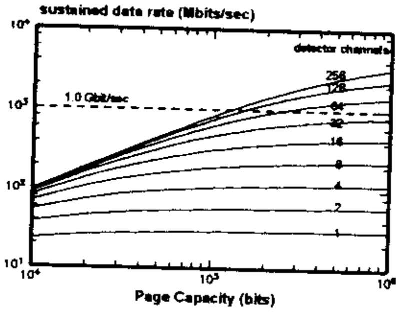
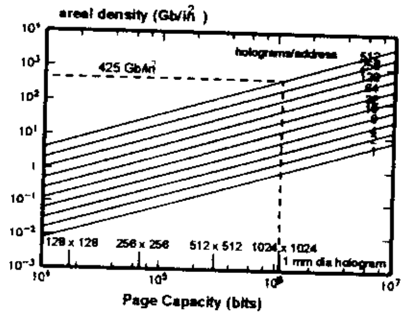
HOLOGRAPHIC DATA RATE & AREAL DENSITY





$$\text{sustained data rate} = \frac{C_p}{\text{access time} + \text{integration time} + \text{read time}}$$

$$\text{integration time} = 5 \times 10^{-19} \frac{n^2\ N\ C_p}{P}$$

$$\text{read time} = \frac{C_p}{m\ r}$$

for figure:

- access time = 100 usec
- P = 1W laser (at medium)
- N = 512 holograms
- n = 1000 photoelectrons
- r = 30 MHz detectors
- m = detector channels
- 663 nm

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BEAM ADDRESSABILITY

Galvanometer (mirrors - mechanical motion)
- millisecond speed at best
- not true random access
- large aperture; large angle
- broad spectral bandwidth

Acousto-optic (nonmechanical motion)
- 10's of microsecond
- random access
- small aperture: small angles
- Bragg-type; diffraction

Phase multiplexing (nonmechanical motion)
- requires a phase SLM
- limited to SLM response times
- cannot do x-y addressing

All
- suited for addressing a stack
- complex optics for x-y addressing

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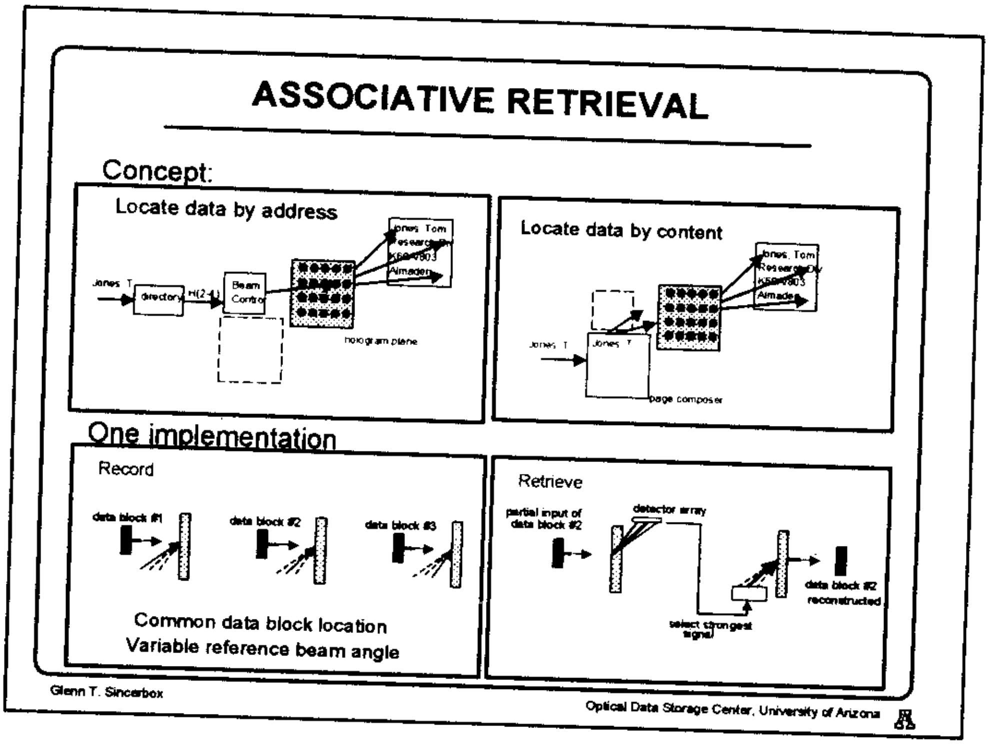

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•B. J. Goertzen and P. Mitkas, "Volume holographic storage for large relational databases," Optical Engineering, 35(7), 1847-1853, (1995).

•L. J. Irakliotis, G. Betzos and P. A. Mitkas, "Optical associative processors" in A. Krikelis and C. Weems, editors, *Associative Processing and Processors*, 155-179, IEEE Computer Society Press, (1997).

•G. W. Burr, S. Kobras H. Hanssen and H. Coufal, "Content-addressable data storage using volume holograms," submitted to Applied Optics, 1999.

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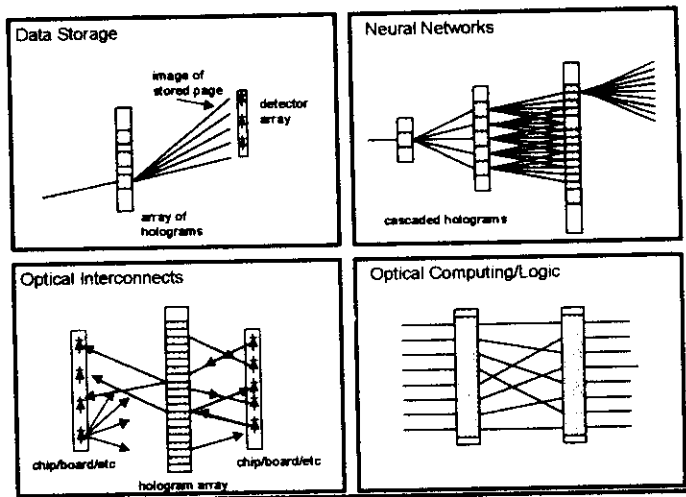
HOLOGRAPHY AS A TECHNOLOGY BASE FOR MANY APPLICATIONS



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POTENTIAL

- Moving light beams → fast random access & low latency
  - staged access
    - <100 msec to Gbit collection of files
    - 10 - 100 usec to any individual Mbit file
- Parallel data transfer → very high data rates
  - 1.0 Gbit/sec within a stack of 1,000 - 10,000 files (pages)
- Storage block multiplexing → very high areal/volumetric density
  - 100 - 500 Gb/in^2 (500 Gb/in3 - 1.5 Tb/in^3)
- High capacities: 100 GB - 10 TB
  - low error rate through redundant storage
- Parallel access → novel processing
  - i.e., fast search engine

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HISTORICAL HIGHLIGHTS

1948	Invention of holography by Gabor
1962-1964	IBM SDD Poughkeepsie Ad. Tech; Standing Wave Read-only Memory
1962	Invention of the laser
1963	Holographic storage principles developed by Van Heerden
1964-1968	IBM SDD Poughkeepsie Ad. Tech; Holographic Beam-addressable memory
1964-1968	Bell Labs photorefractive write-once memory
1966-1968	IBM SDD San Jose Ad. Tech; Computer-generated 1-D memory
1985-1988	IBM GPD Tucson; erasable holographic memory
1988-1991	MCC Bobcat project
1992- present	New companies appear; Tamarack, Accuwave, Holoplex, Optitek
1994	Formation of PRISM (PhotoRefractive Information Storage Materials) Consortium
1995	Formation of the HDSS (Holographic Data Storage Systems) Consortium

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WHAT HAS CHANGED RECENTLY?

- **Development of the enabling technologies**
  - spatial light modulators
  - detector arrays
  - compact laser sources
- **Advances in materials**
  - progress in nondestructive readout
    - lithium niobate doping
    - Two-color recording
  - polymeric materials
- **Novel architectures**
  - phase-encoded multiplexing
  - engineering solutions to hologram volatility
  - peristrophic multiplexing
  - shift multiplexing
- **Better understanding of applications**
  - increasing demand for capacity
  - potential for WORM applications

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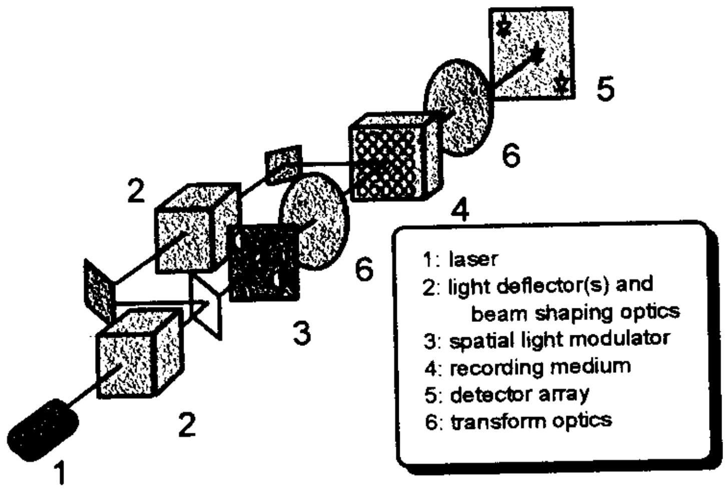
SYSTEM COMPONENTS



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SYSTEM REQUIREMENTS

• Laser ✓ near-ir ✓ 500 mW cw, TEM	**• Beam shaping optics** ✓ low cost, compact ✓ efficient
• Spatial light modulator ✓ 1024 x 1024 ✓ matched in pixel spacing to CCD ✓ high contrast ✓ fast, 1000 frames/sec ➢ multi-channel	**• Recording medium** ✓ idealium
• Random phase mask	**• Detector array** ✓ 1024 x 1024 ✓ matched in pixel spacing to SLM ✓ low noise ✓ fast, 1000 frames/sec ➢ multi-channel
• Light deflection/access method ✓ hybrid, rugged ➢ acousto optic ➢ galvanometer ➢ mechanical motion	**• Transform optics** ✓ low cost, compact ✓ diffractive optics?

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ENABLING TECHNOLOGIES

Spatial Light Modulator

	Number of pixels	Pixel Spacing (um)	Speed (frames/sec)	Data rate (Mb/sec)	Manuf.
Today	640 x 480	42	60	20	Epson (LC)
Future	1024 x 1024	15.6	100	100	IBM (LC)
	848 x 600	17	2000	1000	TI (DMD)
Requirement	1024 x 1024	Match detector array	1000	1000	TBD

Detector Arrays

	Number of pixels	Pixel spacing	Speed (frames/sec)	Channels	Data rate (Mb/sec)	Manuf.
Today	1024 x 1024	14	60	4	80	Thomson
Future	1024 x 1024	12.8	1000	64	1000	Kodak
Requirement	1024 x 1024	Match SLM	1000	64	1000	TBD

Lasers: TEM_{00}

	Wavelength (nm)	Power (cw watts)	Technology
Today	530	4	SHG/NdYAG
Future	680	0.3	AlGaAs, M-MOPA
Requirement	TBD	TBD	TBD

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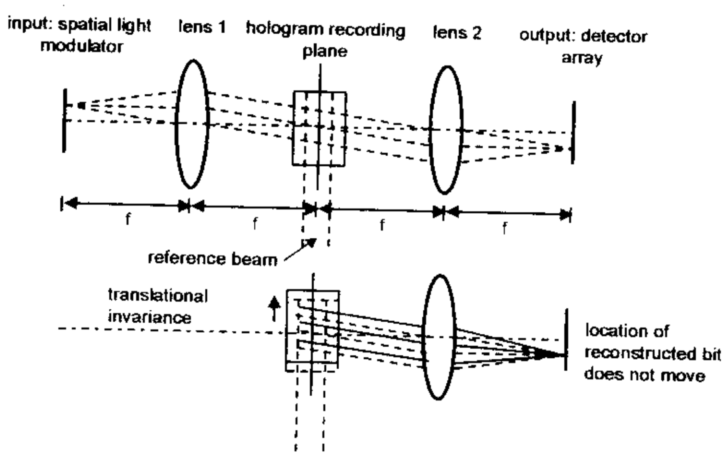
FOURIER TRANSFORM HOLOGRAPHY



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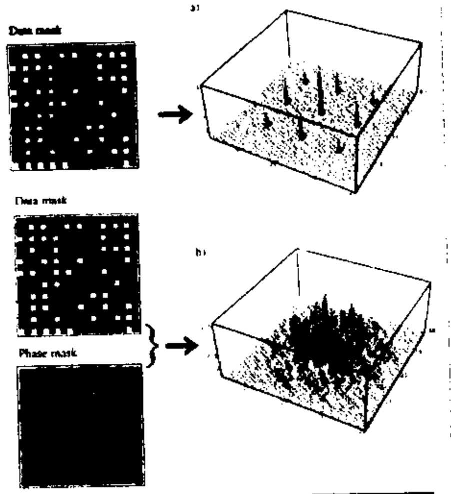
Intensity of the Fourier transform of a random data mask

a) Data mask only
b) Compound of data mask and a two-level phase shifting mask



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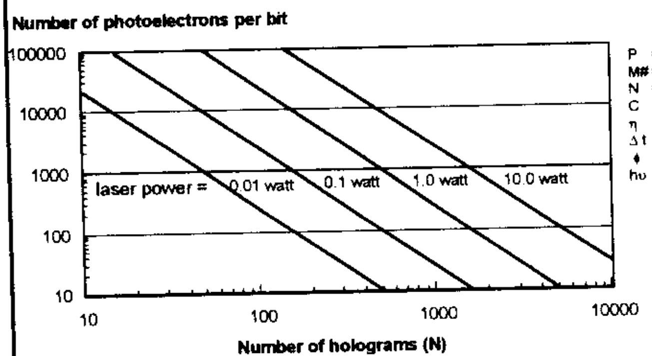
DATA DETECTION

$$n_{photoelectrons} = P_{inc}\left(\frac{M\#^2}{N^2}\right)\eta_{fixing}\left(\frac{1}{C/2}\right)\Delta t_i \phi\left(\frac{1}{h\upsilon}\right)$$



P = incident laser power
M# = media figure of merit (0.5)
N = number of holograms
C = capacity per page (10^6)
η = fixing efficiency (0.5)
Δt = detector integration time (1 msec)
φ = detector quantum efficiency (0.3)
hυ = photon energy (3×10^{-19} 663 nm)

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MATERIAL REQUIREMENTS

Mechanisms:


refractive index change


absorption change


change in thickness or surface relief


combination

Candidates:

- Photographic
- Photoresist
- Photopolymer
- Ablative thin films
- Thermoplastic
- Photochromic
- Phase change
- Photorefractive
- Magneto-optic
- Layered systems

Requirements:

- High optical quality
- Thick:
  500µm -10 mm
- large $\Delta n \sim 10^{-2}$-10^{-3}
- large M#
- Sensitivity
  10^{-2} cm³/joule
- Self-processing
- Fixable
- Near-ir sensitive
- Long shelf life
- Inert
- Cheap

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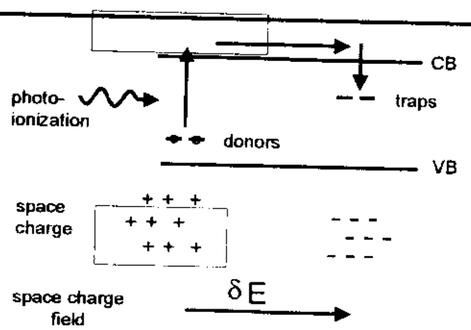
Photorefractive Materials

- Charge generation & trapping = f(dopants)
- Electro-optics & charge transport = f(host)



refractive index modulation $\Delta n = \frac{1}{2} n_b^3 r_{eff} \delta E$

Valley & Klein, Opt. Eng., 22, 704 (1983)

	index change 10^{-6}	sensitivity 10^{-3} cm³/joule
BSO	35	14
$BaTiO_3$	1000	5
SBN	200	0.083
$LiNbO_3$	100	0.050
PVK/TNF/F-DEANST	150	0.019

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Photorefractive Sensitivity
4 ways to measure

1. Change in refractive index per unit of energy absorbed: $S_{n1} = \frac{dn_1}{d(\alpha W_0)}$

2. Change in refractive index per unit of energy incident: $S_{n2} = \frac{dn_1}{dW_0} = \alpha S_{n1}$

3. Change in diffraction efficiency per unit of absorbed energy: $S_{\eta 1} = \frac{d(\eta^{1/2})}{d(\alpha W_0)} \frac{1}{d}$

4. Change in diffraction efficiency per unit of incident energy: $S_{\eta 2} = \frac{d(\eta^{1/2})}{dW_0} \frac{1}{d} = \alpha S_{\eta 1}$

In the early stages of hologram formation: $\eta = \sin^2\left(\frac{\pi \Delta n_1 d}{\lambda \cos\theta_0}\right)^2 \cong \left(\frac{\pi \Delta n_1 d}{\lambda \cos\theta_0}\right)^2$

Hence: $S_{\eta 1} = \frac{\pi}{\lambda \cos\theta_0} S_{n1}$

from: Gunter & Huignard, *Photorefractive Materials and Their Applications I*, Springer-Verlag, 1988

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Typical Sensitivities

	$S_{n1}^{-1}[10^3 J cm^{-3}]$	$S_{n2}^{-1}[10^3 J cm^{-2}]$	$S_{\eta 1}^{-1}[mJ cm^{-3}]$	$S_{\eta 2}^{-1}[mJ cm^{-2}]$
$LiNbO_3$	20 - 200	---	1000	300
$LiTaO_3$	—	---	50	10
$KNbO_3$	6 - 60	0.1	---	—
$BaTiO_3$	.2	---	50 -1000	—
$Sr_{0.4}Ba_{0.6}Nb_2O_6$:Ce	12 - 75	7.2 - 30	2.5 - 15	1.6 - 6
$Bi_{12}SiO_{20}$	0.07 - 0.5	---	5	—

- Gunter & Huignard, *Photorefractive Materials and Their Applications I*, Springer-Verlag, 1988
- Valley & Klein, Opt. Eng., Vol. 22(6), p704-711, (1983)

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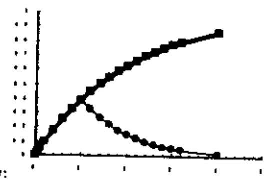
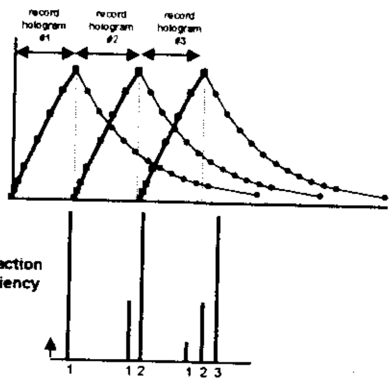
DATA VOLATILITY IN PHOTOREFRACTIVE MATERIALS

Recording:
$\Delta n = \Delta n_s\left(1 - e^{-t/\tau_r}\right)$

Erasure:
$\Delta n = \Delta n_s\left(e^{-t/\tau_e}\right)$

Diffraction efficiency:
$\eta \propto \Delta n^2$





[redacted]

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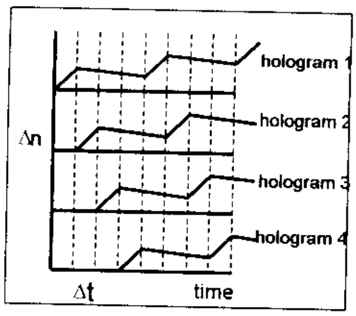
EXPOSURE CONTROL FOR EQUAL EFFICIENCIES

- Scheduled exposure [1] :
  decrease each successive exposure according to:

$$t_N = \tau_r \ln \frac{(1+(N-1)\beta)}{(1+(N-2)\beta)}, \qquad \beta = \frac{\Delta n_0}{\Delta n_m}$$

- Interleaved recording [2] :
  use multiple short exposures in random order.

$$\Delta t = \frac{\tau_e}{2(N-1)} \ln(1+\varepsilon)$$



1: Blotekjaer; Psaltis, et al; Maniloff, et al
2: Taketomi, et al

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EXAMPLE OF DATA VOLATILITY

- Equal exposure times

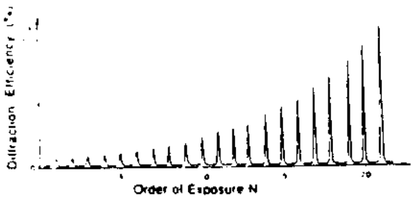

Fig. 2 Diffraction efficiency versus the order of exposure, N, before compensation. The reference-to-object beam ratio $K = 1$.

- Scheduled exposure

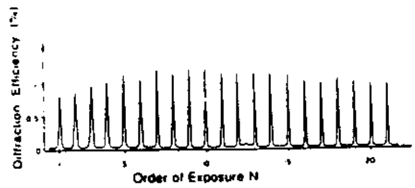

Fig. 3. Diffraction efficiency versus the order of exposure after compensation, with $K = 1$.

From Maniloff et al

Diffraction Efficiency Considerations

diffraction efficiency: $\eta = \sin^2 \frac{\pi \Delta n d}{\lambda \cos\theta}$

refractive index growth: $\Delta n_0 = \Delta n_m \left(1 - e^{\frac{t_N}{\tau_r}}\right)$

recording schedule: $t_N = \tau_r \ln\left(\frac{1+(N-1)\beta}{1+(N-2)\beta}\right)$

combining: $\eta = \sin^2 \frac{\pi \Delta n_m d}{\lambda \cos\theta}\left(\frac{\beta}{1+(N-1)\beta}\right) \propto \boxed{\frac{1}{N^2}}$

i.e., efficiency for 1,000 holograms = efficiency for 1 hologram / 1,000,000

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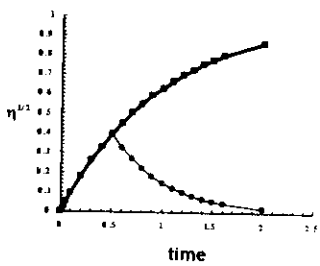
M-NUMBER



growth: $\left(1 - e^{\frac{-t}{\tau_r}}\right)$

decay: $e^{\frac{-t}{\tau_e}}$

$$\eta = \left[\left(\frac{A_0}{\tau_r}\right)\frac{\tau_e}{M}\right]^2 = \left(\frac{M/\#}{M}\right)^2$$

$$M/\# = \left(\frac{A_0}{\tau_r}\right)\tau_e$$

Typical M/#

	Data	Plane waves
$LiNbO_3$	0.5 - 1.0	1.5 - 20
KLTN		4 - 25
SBN		70
Polymer		15

Mok, Burr and Psaltis, Opt. Lett., Vol. 21 (12), p896 (1996)

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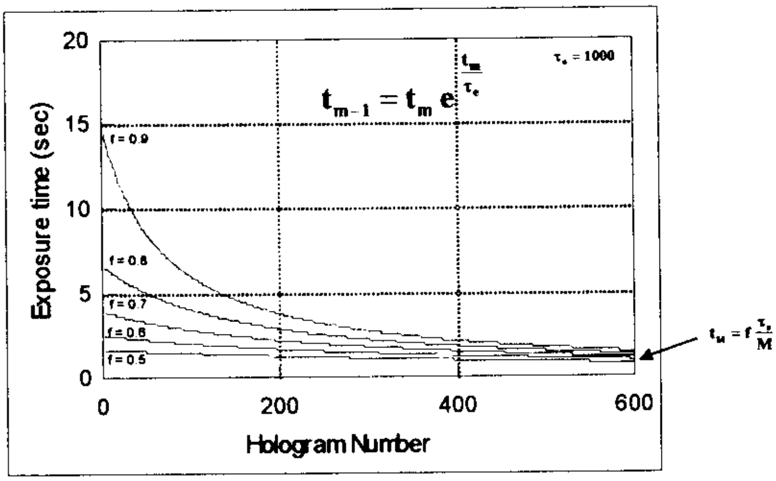
M-NUMBER BASED SCHEDULE



diffraction efficiency: $\eta = f^2\left(\frac{M/\#}{M}\right)^2$

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SOLUTIONS TO DATA VOLATILITY

Conversion to a less-mobile species (fixing)
- thermal (ions)
- electrical (domains)

Gated recording/reading
- 2-color

Novel engineering solutions
- optical, electrical feedback

Irreversible photochemistry
- read-only
- write-once-read-many (WORM)

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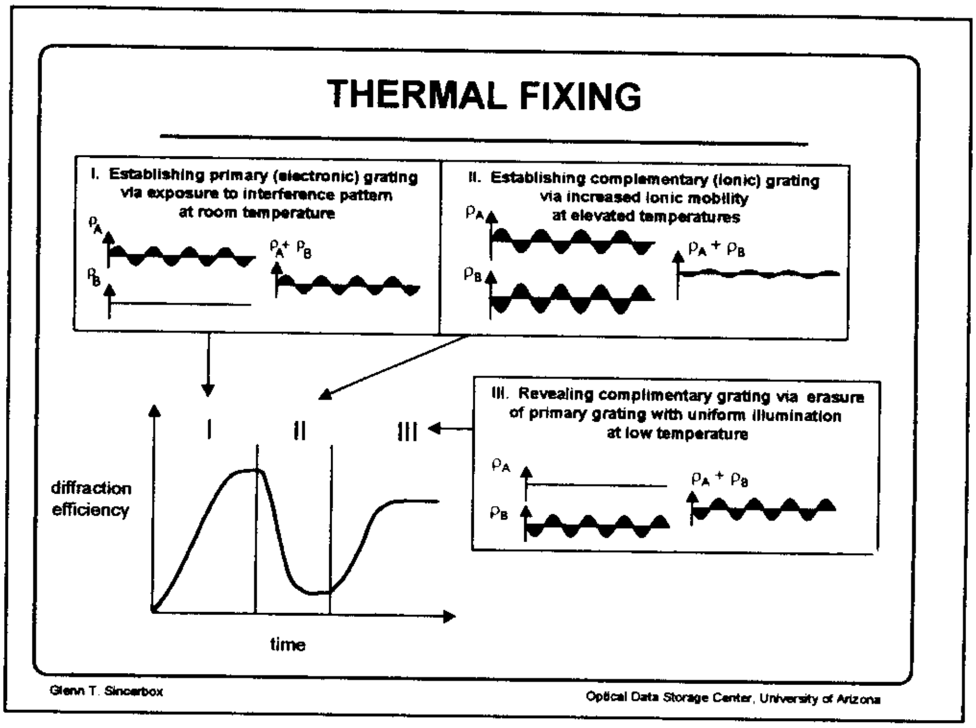
THERMAL FIXING
I. Establishing primary (electronic) grating via exposure to interference pattern at room temperature
II. Establishing complementary (ionic) grating via increased ionic mobility at elevated temperatures
III. Revealing complimentary grating via erasure of primary grating with uniform illumination at low temperature
ρA
ρB
ρA + ρB
diffraction efficiency
time
I
II
III
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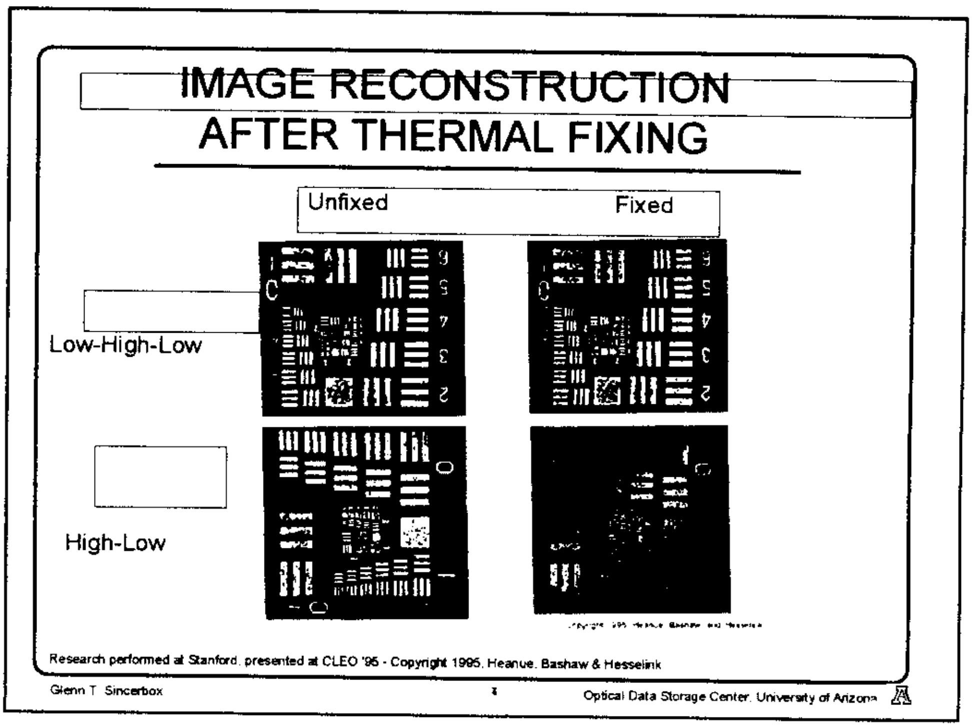
IMAGE RECONSTRUCTION AFTER THERMAL FIXING
Unfixed
Fixed
Low-High-Low
High-Low
Research performed at Stanford, presented at CLEO '95 - Copyright 1995, Heanue, Bashaw & Hesselink
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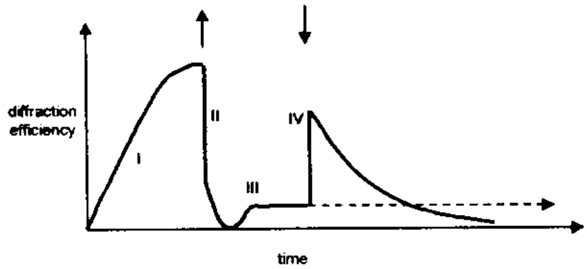
ELECTRICAL FIXING



I. exposure: establish space charge field

II. fix: pulsed application of external field: - 2kV/cm
- exceed H_c
- creates domains

III. read
- erases part of space charge field
- lower efficiency, long lived

IV. electrical revealing
- repole crystal, reveal space charge grating
- optically erased

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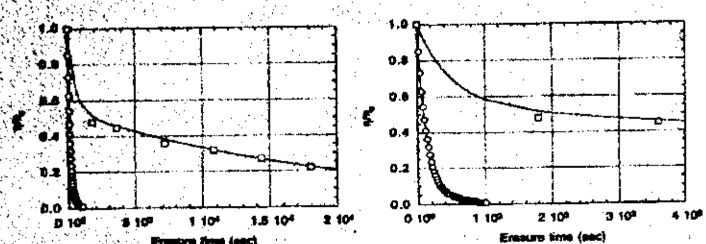
Fixed Grating Decay with Constant Erasure

$\eta = r_1 \exp(-t/t_1) + r_2 \exp(-t/t_2)$

Erasure without fixing, Fitted with r_1=0.97, r_2=0.03, t_1=308s, t_2=1,450s

Erasure with fixing, Fitted with r_1=0.45, r_2=0.55, t_1=1,000s, t_2=40,000s



With Constant Erasure at 50 mW/cm²

Rockwell Science Center

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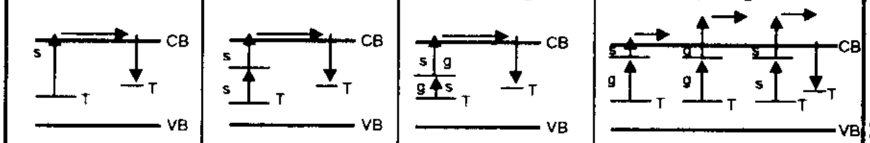
RECORDING OPTIONS

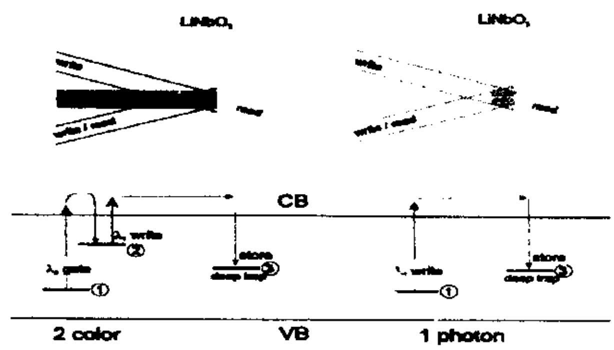
1-photon	2-photon $\omega_1 = \omega_2$	2-color $\omega_1 > \omega_2$	mixed $\omega_1 < \omega_2$
no gating	no gating	true gating	gating bkgnd no gating



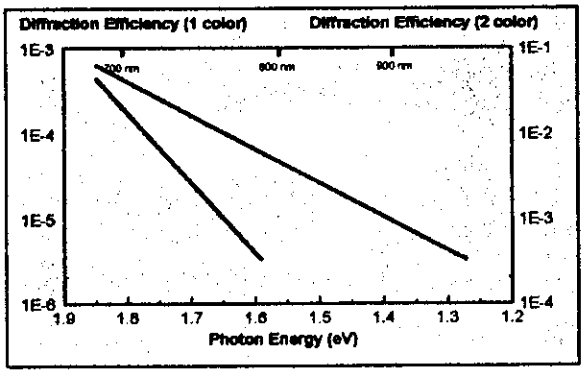
Gated recording:

- pump material with light at first wavelength
  - → light carries no information - serves only as a gate
- form hologram at second wavelength
- read hologram at second wavelength without gate
- erase hologram with both wavelengths

Two-color holographic gratings



TWO-COLOR RECORDING



research performed at SRI

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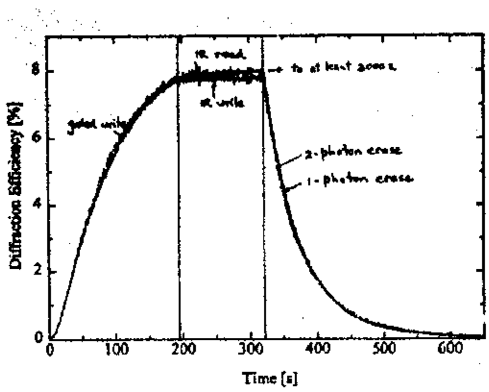
2 - COLOR GATING

LiNbO$_3$:Pr

write: 800 nm, 25+25 W/cm^2

gate: 488 nm, 25 W/cm



research performed at IBM

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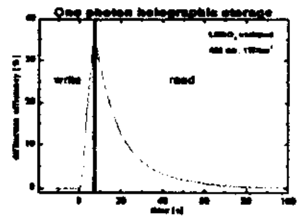
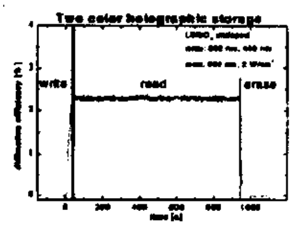
Reading holograms in 1-photon and 2-color schemes



writing: green
reading: green



sensitizing: green
writing: red
reading: red

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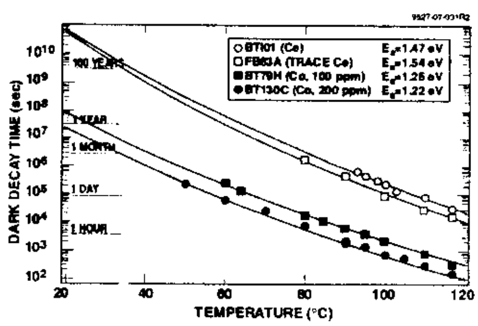
Dark Decay in $BaTiO_3$



G.D. Bacher *et al.*, Optics Letters 21, 18-20, 1996.

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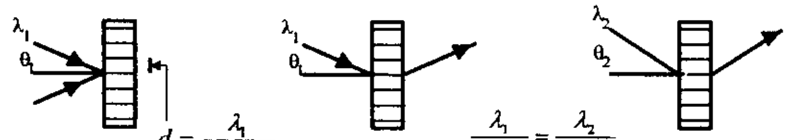
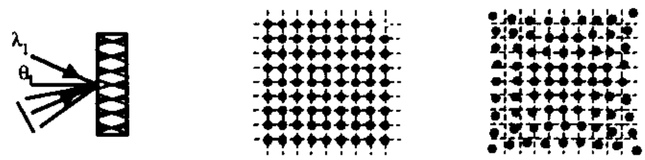
NONDESTRUCTIVE READOUT AT ANOTHER WAVELENGTH

Bragg Effect - plane waves:



$d = \frac{\lambda_1}{n \sin\theta_1}$ Read at λ_1 $\frac{\lambda_1}{\sin\theta_1} = \frac{\lambda_2}{\sin\theta_2}$ Read at λ_2

Extended object can only be Bragg-matched for one ray:



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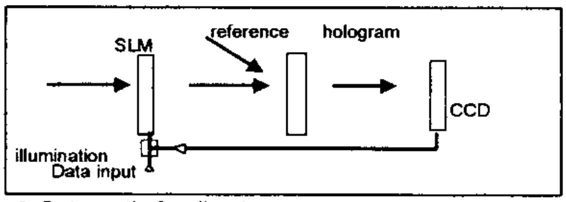
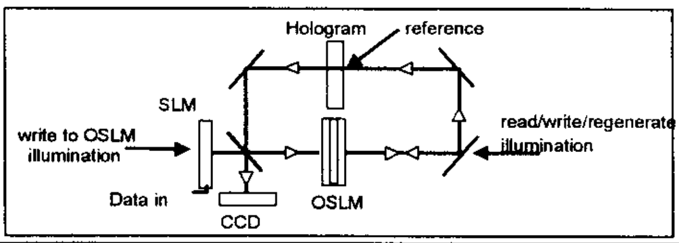
CONTROL OF DESTRUCTIVE READOUT

- Buffer data and feedback
  - Electronic feedback



  - Opto-optic feedback

Boj, Pauliat & Roosen, Opt. Lett., 17, 438 (1992).



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ENGINEERING SOLUTIONS TO VOLATILITY

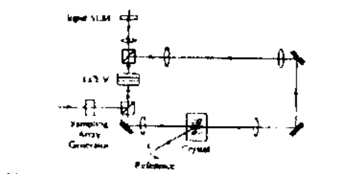
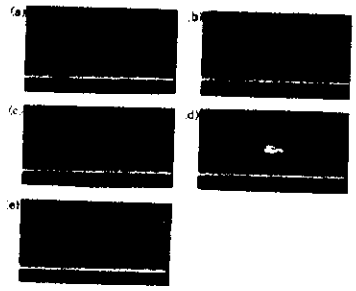


Fig. 1 Schematic diagram of the sampled dynamic holographic memory



(a) record 10 holograms, equal exposure
(b) after dynamic copying for 27 cycles
(c) erasure of 5th hologram with 180 reference beam phase shift
(d) dynamic copying to rejuvenate other 9 holograms
(e) writing of new hologram in 5th position with dynamic equalization

Y. Qiao & D. Psaltis, Opt. Lett. 17 (19), 1992

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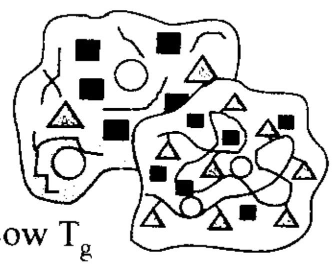
PHOTOREFRACTIVE POLYMER DESIGN

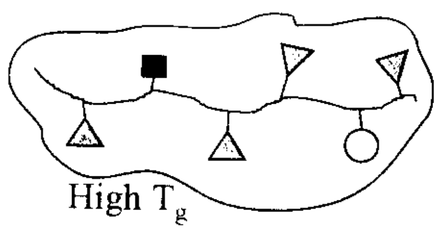
Requirements:

- photosensitivity
- photoconductivity
- trapping
- electro-optic properties

Guest/Host approaches



Fully functionalized approach



Viewgraph courtesy of Dr. Bernard Kippelen, University of Arizona

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Optical Data Storage Center, University of Arizona

Holographic Storage

Material requirements	Current status
> 1 mm thick	100 - 200 μm
high Δn	Δn ≈ 0.01
670-850 nm	488 - 830 nm
high optical quality	phase stability
low scattering	zero birefringence matrix
1 ms response time	> 100 ms
non-destructive read-out	TPA photorefractive polymers

Viewgraph courtesy of Dr. Bernard Kippelen, University of Arizona

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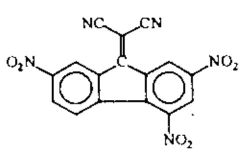
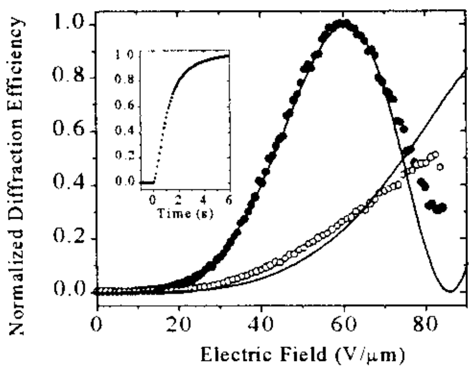
NEAR IR SENSITIVITY

Science, 279, 54 (1998)



830 nm



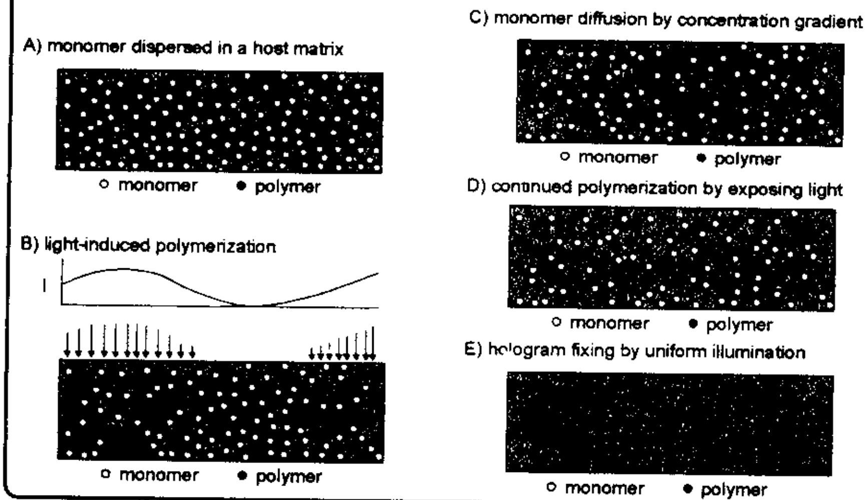
DHADCMPN:PVK:ECZ:TNFDM (25:49:24:2 % wt.)

Viewgraph courtesy of Dr. Bernard Kippelen, University of Arizona

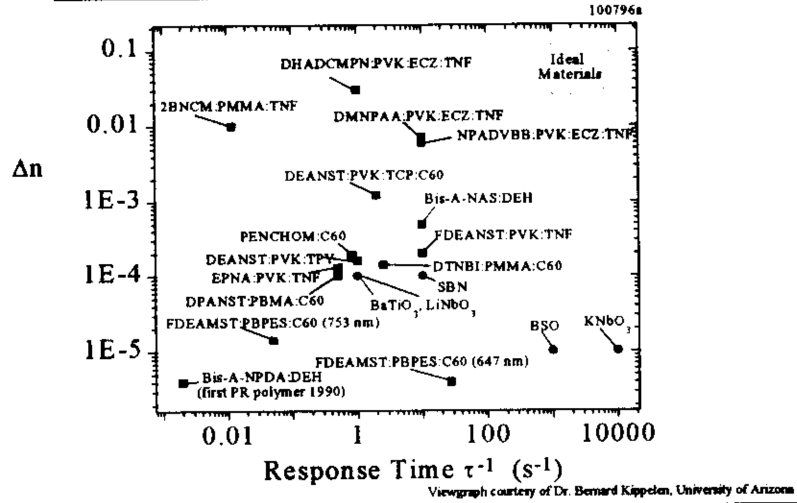
Glenn T. Sincerbox

Optical Data Storage Center, University of Arizona

HOLOGRAPHY VIA PHOTOPOLYMERIZATION



ORGANIC & INORGANIC PHOTOREFRACTIVE MATERIALS

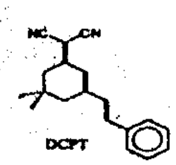


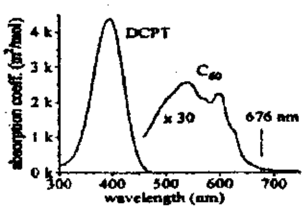
Viewgraph courtesy of Dr. Bernard Kippelen, University of Arizona

Glenn T. Sincerbox

Optical Data Storage Center, University of Arizona

PHOTOCHROMIC POLYMERS





Mechanism:

- Selective photoexcitation of sensitizer molecules
- Energy transfer (triplet-triplet) from sensitizer to chromophore
- Photoreaction of chromophore with accompanying index change

Features:

- WORM material
- large Δn: 0.002
- sensitive at 676 nm
- sensitivity: 0.01 cm³ /kJ ($LiNbO_3$: 0.02 cm³ /kJ)
- 100 holograms multiplexed in 150 micron sample
- solvent-free fabrication (1mm thickness possible)

R. Wortmann, et. al., Appl. Phy. Lett., 69 (12), 1996

Glenn T Sincerbox

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Lucent photopolymer strategy

Matrix
- In situ matrix formation (thick media, flatness)
- Cross-linked matrix (stable support)
- Compatibility with monomer (low scatter)
- Robust polymer backbone (environmental)

Monomer Photochemistry
- Chemistry independent from matrix formation (Δn contrast)
- High contrast with low shrinkage
- Efficient photochemistry (sensitivity)
- Compatible with matrix (low scatter)

07/02/99 A. Harris/L. Dhar Lucent Technologies Bell Labs Innovations

Holographic WORM Media Requirements

Performance
- Dynamic Range - High storage density with rapid read rate
  - -Refractive Index Contrast (Δn) } M/#
  - -Thickness } M/#
  - -Low scatter
- Media Thickness - Low crosstalk of multiplexed holograms
- Photosensitivity (visible - near-IR) - High write rate
- Optical Quality - Low BER imaging of digital data pages

Cost
- Low Cost

Stability
- Dimensional Stability - High fidelity data recovery
- Nonvolatile Readout
- Solvent/Heat-Free Processing
- Long Archival Life (5-10 years)
- Environmental and Thermal Stability

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Lucent Holographic WORM Media Status, mid-1999

Performance	**Goal**	**Status**
Key performance parameters met		
▫ Dynamic Range (M#)	15	~20
▫ Chemical shrinkage..................	0.1%	0.1%
▫ Thickness	1 mm	1 mm
▫ Scatter	~1e-6	>~1e-6
▫ Photosensitivity (532 nm) (total exposure dose)	~500 mJ/cm^2	~350 mJ/cm^2
▫ Optical Quality	<(λ/2)/cm	<(λ/4)/cm

Stability

Key stability issues under investigation

- ▫ Tested shelf life .... >Months
- ▫ Archival life of high density digital data ... Under investigation
- ▫ Environmental .... Sealed cell
- ▫ Thermal Dimensional Stability ...... Temp control drive

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Lucent Holographic Photopolymer Date Storage Status

Photopolymer material meeting key performance requirements for high density digital storage

- -dynamic range
- -writing-induced dimensional change
- -scatter and optical quality
- -sensitivity

Demonstration of Digital Data Storage & Recovery

>3000 Digital Data Pages @ 48 bits/μm^2

Next Steps

-Demonstrate higher density in newest materials (100 bits/um2)
-Systematic investigation of thermal/environmental stability
-Demonstrate archival stability of high density digital data
-Manufacturable low-cost media strategy

07/02/99 A. Harris/L. Dhar Lucent Technologies Bell Labs Innovations

IBM HOST TESTSTAND

Computer-controlled precision teststand
- Fourier transform (4f) optics
- 1024 x 1024 bit masks (random)
- 1:1 imaging onto detector array
- 14 bit image capture
- 25-335 degree reference angles
- interferometric stability (20 nm)
- multi-wavelength (Ar, Kr lasers)
- menu-driven writing & reading
- 15 translation/rotation stages
- laser power, polarization control
- multiple sample configurations
- extremely low intrinsic bit error rate

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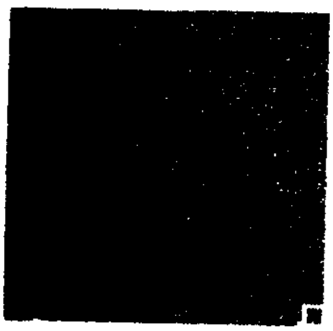
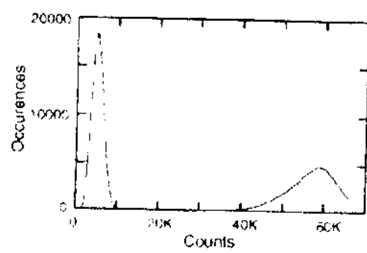
IBM HOST
IBM Holographic Optical Storage Team

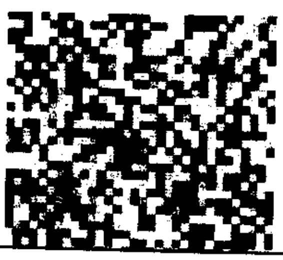
High Resolution Image of 256 kbit Data Page



Histogram



Shown above is a 512 x 512 pixel data mask, imaged through the HOST tester.
At right, a 1kb portion is expanded to shown individual data bits.

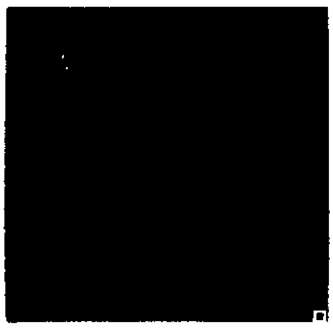


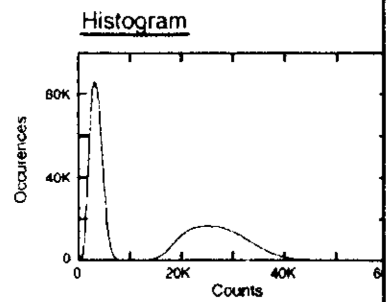
18 μm data pixel spacing

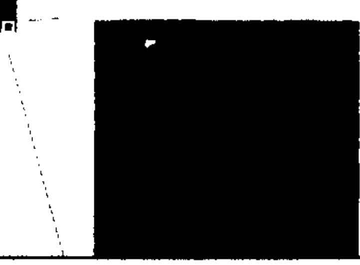
Overall image size = 0.92cm

ARPA
IBM HOST
IBM Holographic Optical Storage Team

High Resolution Image of 1 Megabit Data Page





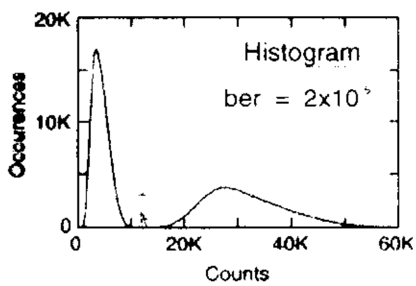


9 µm data pixel spacing

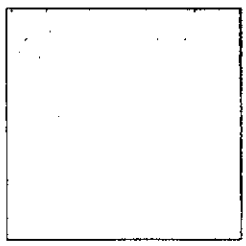
Overall image size = 0.92cm

Shown above is a 1024 x 1024 pixel data mask, imaged through the HOST tester.
At right, a 1kb portion is expanded to shown individual data bits.

Holographic Storage: Reconstructed 256 kbit Data Page in $LiNbO_3$



Map of "ambiguous" pixels.
(Within intensity range shown)



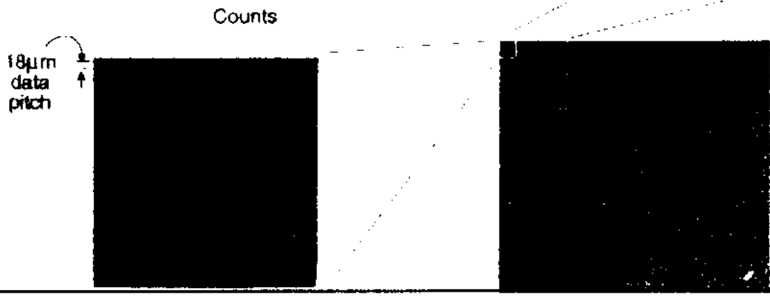


Image size = 0.92cm

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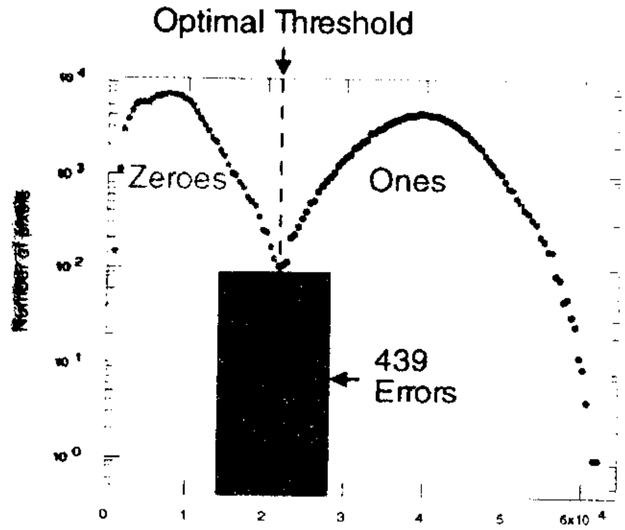
IBM HOST

Bit Error Rate of a Poor Image

$\delta M = 8 \times 10^{-4}$



$$BER = \frac{\text{Errors}}{\text{Total Bits}} = \frac{439}{262{,}144} = 1.67 \times 10^{-3}$$

Lithium Niobate: "Best to Date"

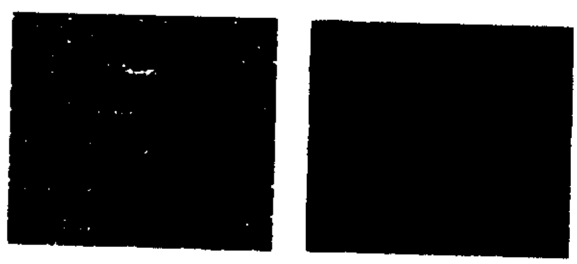
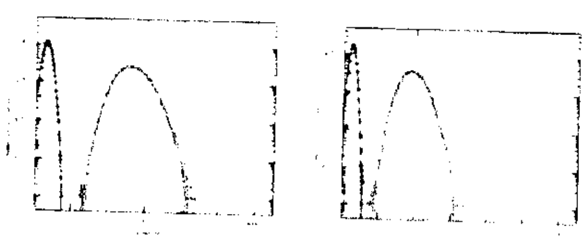
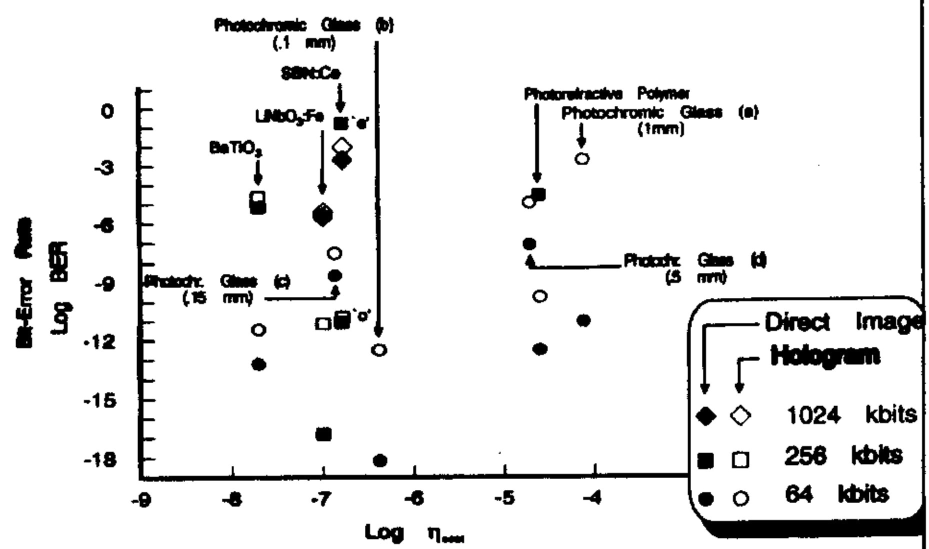


Image: 10

Hologram: 8. x 10



Optical Quality Limits to Performance



FACTORS INFLUENCING BER

raw ber ⇨ signal / noise ⇨

diffraction efficiency
No. bits/pages
No. pages/volume
M number
wavelength
etc

---

scattering
misalignment
distortions (fixed & optically induced)
diffraction spreading
crosstalk (intra, inter)
electronic
etc

Glenn T. Sincerbox — Optical Data Storage Center, University of Arizona

If you recover data with no errors *then you are not trying hard enough* to optimize storage capacity

raw ber 10^{-5} $\xrightarrow[\text{error-correcting codes}]{\text{modulation codes}}$ corrected ber 10^{-12}

ber is a measure of the utility of the technology

$$\frac{\text{cost}}{\text{Mbyte}} \Longrightarrow \frac{\text{margins}}{\text{capacity}}$$

BER & SNR

Combination of Rician (optical) & Gaussian (electrical) statistics:

$$ber = \frac{1}{2} erfc\left(\frac{v_{th}}{\sqrt{2}\sigma_e}\right) + \frac{1}{2} erfc\left(\frac{\sigma_e}{2\sqrt{2}\sigma_A^2} - \frac{v_{th}}{\sqrt{2}\sigma_e}\right) \exp\left(-\frac{v_{th}}{2\sigma_A^2} + \frac{\sigma_e}{8\sigma_A^4}\right)$$

for pure electrical noise: $\sigma_A = 0$, $v_{th} = 1/2$, $snr = 1/\sigma_e$

$$ber = \frac{1}{2} erfc(.354\ snr)$$

for pure optical noise: $\sigma_e = 0$, $v_{th} = 1/4$, $snr = 1/2\sigma_A$

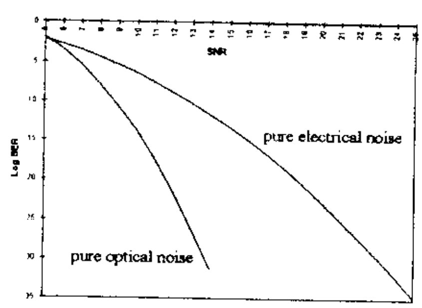
$$ber = \exp\left(-\frac{snr^2}{2}\right)$$

σ_A^2 = variance of complex noise amplitude

σ_e^2 = variance of electrical noise

$$v_{th} = \frac{2\sigma_A/4 + \sigma_e/2}{2\sigma_A + \sigma_e}$$

$$snr = \frac{1}{\sqrt{4\sigma_A^2(1+\sigma_A^2) + \sigma_e^2}}$$



from C. Gu, F. Dai, and J. Hong, Electronics Letters, Vol. 32, No. 15, p1400, (1996)

ber and margins

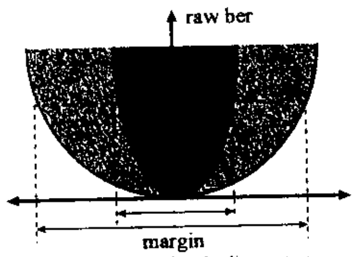
- ber is a measure of the utility of the technology

$$\frac{\text{cost}}{\text{Mbyte}} \Rightarrow \frac{\text{margins}}{\text{capacity}}$$

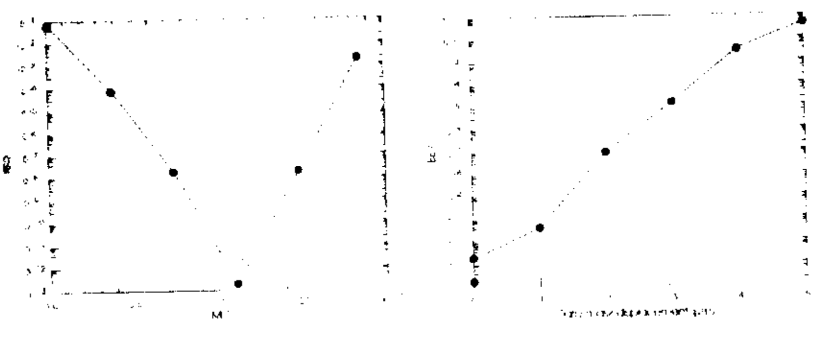
- how difficult is it to achieve desired performance?

margins ⇒ mechanical tolerances, optical tolerances, electrical tolerances

- the *bathtub* curve



DEPENDENCE OF BIT ERROR RATE ON MAGNIFICATION AND ALIGNMENT



512x512 random bits on 18 µm centers

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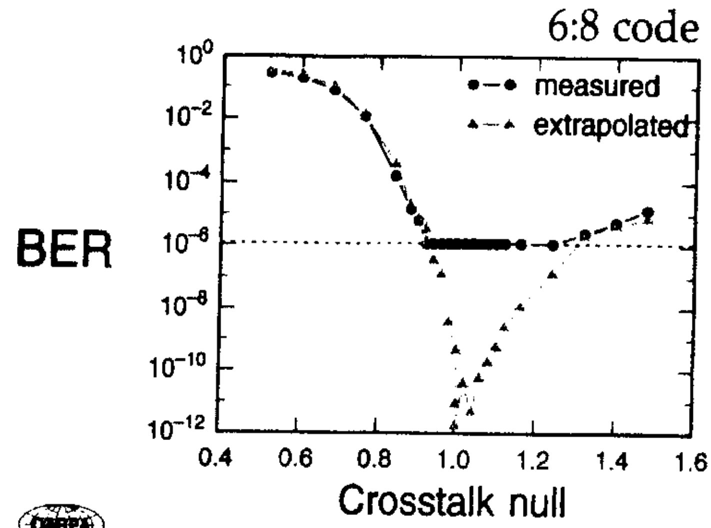
Optical Data Storage Center, University of Arizona



IBM HOST

Each point represents the average BER of 45 holograms at the given angular spacing

PATHWAYS TO IMPROVING THE RAW BER

- Increased signal
  - ✓ more photons/bit
- Reduced noise
  - ✓ better optical quality
- Better (or more forgiving) alignment
  - ✓ over-sampling(?)
- More uniform illumination of SLM
  - ✓ top hat beams
  - ✓ exposure compensation
- More uniform illumination of hologram
  - ✓ phase mask

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Novel properties of a holographic image
- a coding opportunity -

- Error asymmetry:
  0 -> 1 more likely than 1 -> 0
    1 -> 0 requires exact interference of light
    0 -> 1 can happen with any stray light

- The light on a detector depends on the number of 1's in a data page

$$S_d \propto \frac{\eta}{N_1} \propto \frac{(\Delta M)^2}{N_1} \propto \frac{\left(\frac{N_1 I_1}{I_R}\right)^2}{N_1} \propto N_1$$

Use a code that has a constant number of 1's and 0's

Simple case: 1=  0= 

better choice: 6 user bits can be coded as 8 channel bits so that there are always 4 bits on (1's) and 4 bits off (0's)

N!/R!(N-R)!=70

- Count the 1's for initial error detection

POTENTIAL APPLICATIONS

***Key:* exploit the attributes of holographic storage**

- read data rate
- fast, random access
- capacity through multiplexing
- novel function

Enable new applications

- Image libraries/servers
  medical, on-line catalogs, video-on-demand
  satellite, geophysical,......
- Rapid search engines

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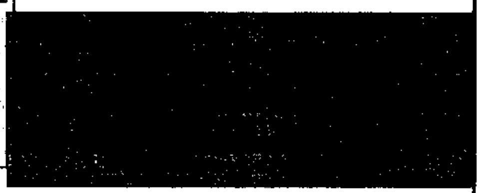
HDSS Applications

rapid, random access to large databases
of very high quality digital images and data

- **Remote sensing - time evolution of images**
  medical images - x-ray, CAT, MRI
  environmental sensing
  resource exploration
  satellite & terrestrial surveillance
  military situation maps
  intelligence gathering
  space exploration



- **Sensor & system logs**
  automotive & aircraft systems
  process plants
  pharmaceutical testing

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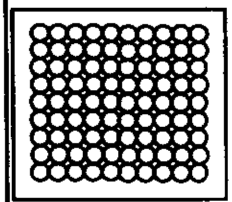
HOLOGRAPHIC LIBRARY FILE

a preliminary view

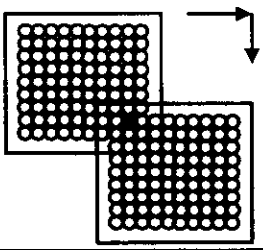


N x M array of holographic 'stacks'
Each stack contains 2000 holograms
Each hologram contains 1Mbit:

larger xtals may be composites

Capacity GBytes	Stacks (N*M)
100	400
1,000	4,000
5,000	20,000
10,000	40,000

Mechanical access (x-y) to stacks,
Nonmechanical access (a-o) within stack; 10-100 μsec



Capacity (GB)	Area cm^2	Mass (kg)	Access time 1/3 band (msec)*	Access time Adjacent (msec)*
100	16	0.048	35	10
1,000	160	.48	150	20
5,000	800	2.4	440	34
10,000	1600	4.8	700	43

* power = 1.0 watt

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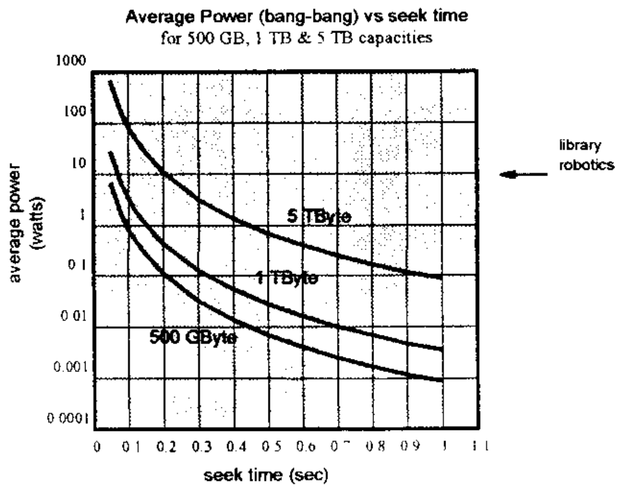
MECHANICAL ACCESS TO HOLOGRAPHIC FILES



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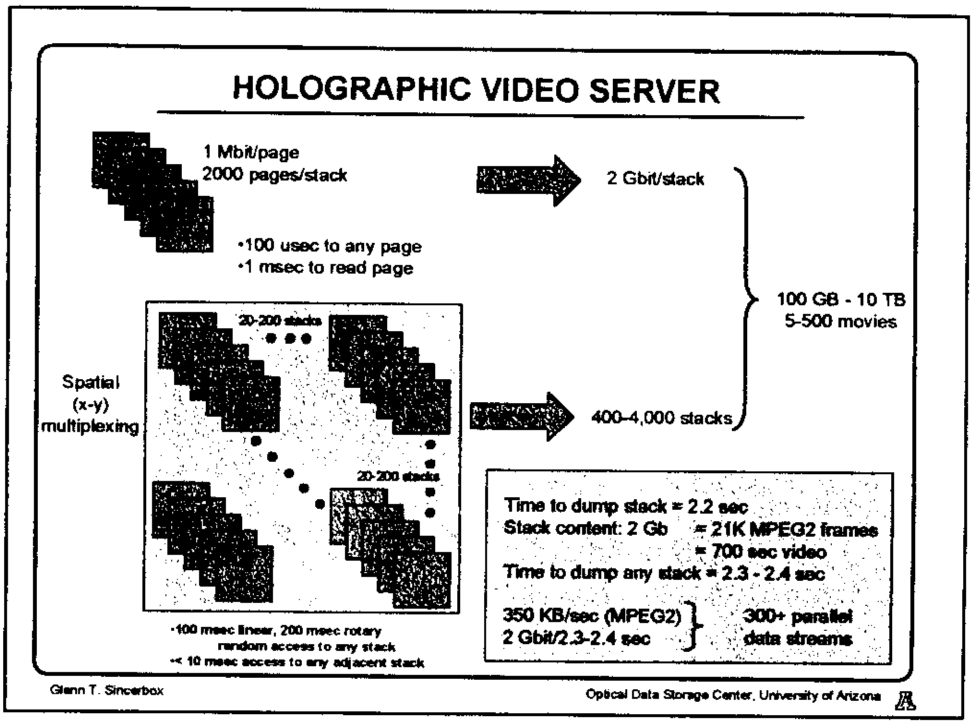
HOLOGRAPHIC VIDEO SERVER
1 Mbit/page
2000 pages/stack
2 Gbit/stack
•100 usec to any page
•1 msec to read page
100 GB - 10 TB
5-500 movies
20-200 stacks
Spatial
(x-y)
multiplexing
400-4,000 stacks
20-200 stacks
Time to dump stack = 2.2 sec
Stack content: 2 Gb = 21K MPEG2 frames
= 700 sec video
Time to dump any stack = 2.3 - 2.4 sec
350 KB/sec (MPEG2)
2 Gbit/2.3-2.4 sec
300+ parallel
data streams
•100 msec linear, 200 msec rotary random access to any stack
•< 10 msec access to any adjacent stack
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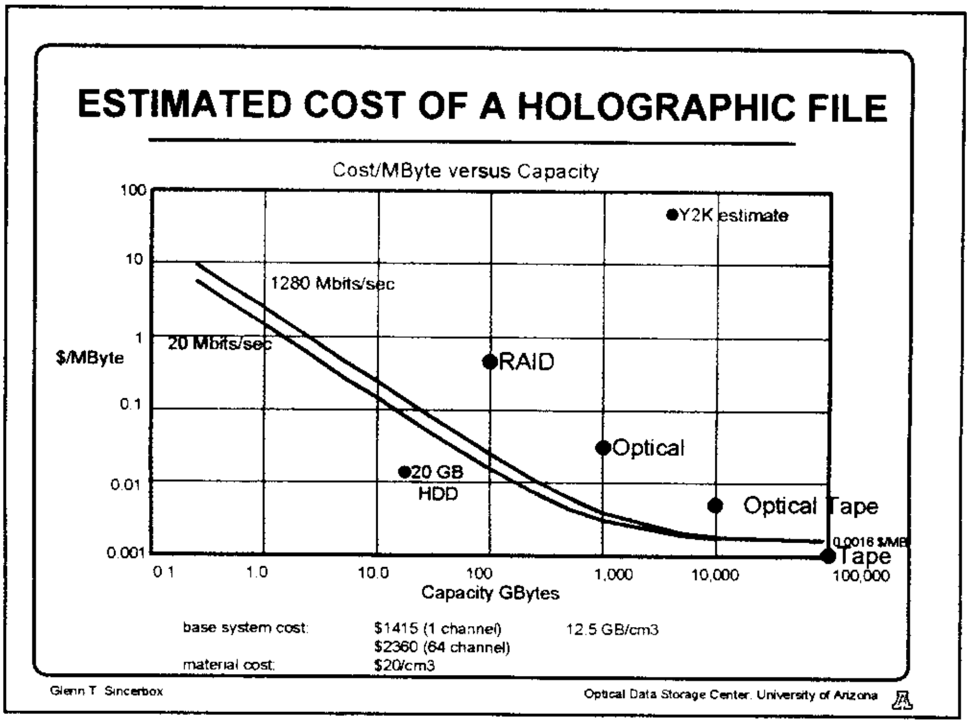
ESTIMATED COST OF A HOLOGRAPHIC FILE
Cost/MByte versus Capacity
$/MByte
100
10
1
0.1
0.01
0.001
Y2K estimate
1280 Mbits/sec
20 Mbits/sec
RAID
Optical
20 GB
HDD
Optical Tape
0.0016 $/MB
Tape
0.1
1.0
10.0
100
1,000
10,000
100,000
Capacity GBytes
base system cost: $1415 (1 channel) 12.5 GB/cm3
$2360 (64 channel)
material cost: $20/cm3
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Optical Data Storage Center, University of Arizona

HOLOGRAPHIC STORAGE CAPACITY ENHANCEMENT

- 2 & 3 dimensional nature of stored pages provides unique opportunity for the development of novel:
  - modulation codes
  - error-correcting codes
- Develop through an understanding and characterization of noise sources:
  - inter-symbol interference
  - inter and intra-page crosstalk
  - data retrieval asymmetry
  - burst/block errors
  - SLM/detector alignment
  - forbidden data patterns
  - code constraints

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MORE NEW NEWS

Signs that the technology is maturing

- **increased activity beyond the proof-of-concept**
- **measurement of bit error rate**
- **development of modulation/demodulation codes**
- **development of error-correcting codes**
- **local thresholding**
- **precompensation/predistortion**
  - **removal of deterministic spatial variations**
  - **shaping/apodizing reading wavefront**
  - **grey-scale considerations**

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HOLOGRAPHIC STORAGE ISSUES

Technology Issues

- WORM materials need more development
  shrinkage, scattering, thickness
- Erasable material systems still not optimized
  develop better methods for nondestructive read
  scale-up, lifetime, stability, cost, optical quality not quantified
- Enabling component technologies drive by video requirements
  CCD & SLM use serial I/O
  block transfer needs parallel I/O
- Nonmechanical accessing methods yet to be developed
- Optics must be simplified

System Issues

- know trade-offs between capacity, data rate, BER, etc.
- identifying the initial markets and the right window of opportunity
- configuring a cost-competitive design

Glenn T. Sincerbox

Optical Data Storage Center, University of Arizona

SUMMARY

* Storage requirements are exploding
* Renewed interest in holographic storage
  - supported by new news
  - place in storage hierarchy
* Government funding encourages formation of industry/university consortia
* High risk - potentially high payoff

Glenn T. Sincerbox

Optical Data Storage Center, University of Arizona

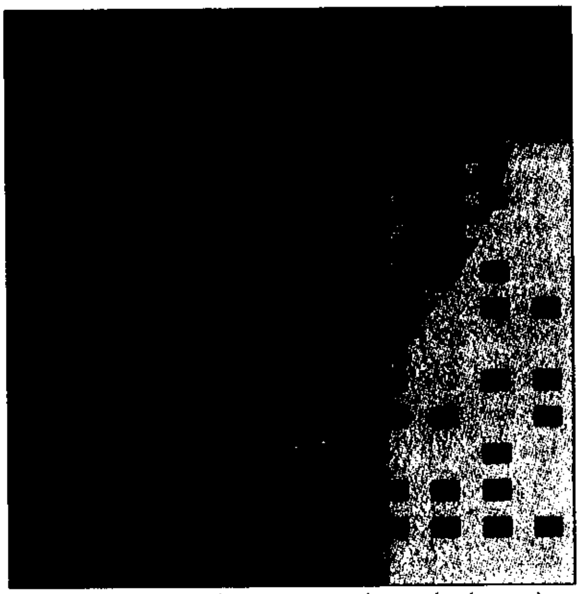
Holographic storage: Ready for prime time?

Glenn Sincerbox, University of Arizona

WITH BETTER MATERIALS AND LASERS, HOLOGRAPHIC STORAGE NO LONGER NEEDS TO RELY ON SMOKE AND MIRRORS

Storage requirements are exploding. By the year 2000, our storage needs will exceed 12 exabytes (10^{20} bits). At 1¢ per megabyte, that translates into a $120 billion business! The amazing advances that have been made in storage technology have abetted this enormous appetite for storage. New storage devices have entered the market place, from ZIP drives to DVD.

These technologies share some common attributes: they are disk-based and hence rely on mechanical rotation and linear storage density to provide adequate data rates; access time also depends on a combination of disk rotation (latency) and linear translation of the head assembly (seek); and finally the data is recorded as localized, discrete marks on a medium that is thinner than one micron. Faster access, higher data rates, and redundant storage of data within the volume of a thicker medium requires a new paradigm in storage. Optics and the basic principles of holography are a particularly attractive way to meet these requirements and may well represent the storage solution of the future.



Most technologies spend decades in research labs before they enter the market. Holography will be no exception to the rule. Invented in 1948 by Dennis Gabor as a way to magnify x-ray images, it wasn't until the invention of the laser in the early 1960s, that holography became practical for storing and retrieving images. But, despite considerable effort, holographic storage never made the business impact that was expected. However, new materials coupled with a better understanding of how to leverage holographic storage may renew interest in this 30-year-old technology.

In magnetic and conventional optical recording, an individual data bit is represented by a localized change in some physical property such as the reversal of a magnetic domain. Holographic recording, in contrast, distributes a single bit throughout the recording volume; thus, there's no correlation between an information bit and a microscopic element in the medium. Light from a signal beam interferes with light in a reference beam to create a three-dimensional pattern of high and low intensity. The recording medium samples this pattern to produce a similar variation in an optical property, such as absorption or refractive index. Recorded structures contain information about the beams' amplitude and phase. When illuminated with a duplicate of the reference beam, the light becomes diffracted, recreating the signal beam. Stored data can be viewed directly or imaged onto a detector array.

In contrast to conventional holography, where scattered light from a three-dimensional scene or object is recorded and subsequently reconstructed for viewing, holographic storage employs a spatial-light modulator (SLM) as a light source. The modulator displays a two-dimensional pattern of 'ones' and 'zeros' that acts like miniature shutters, which represent the stored data. Because each data bit is distributed in three dimensions throughout the recording media, holographic media is less sensitive to material defects than conventional media.

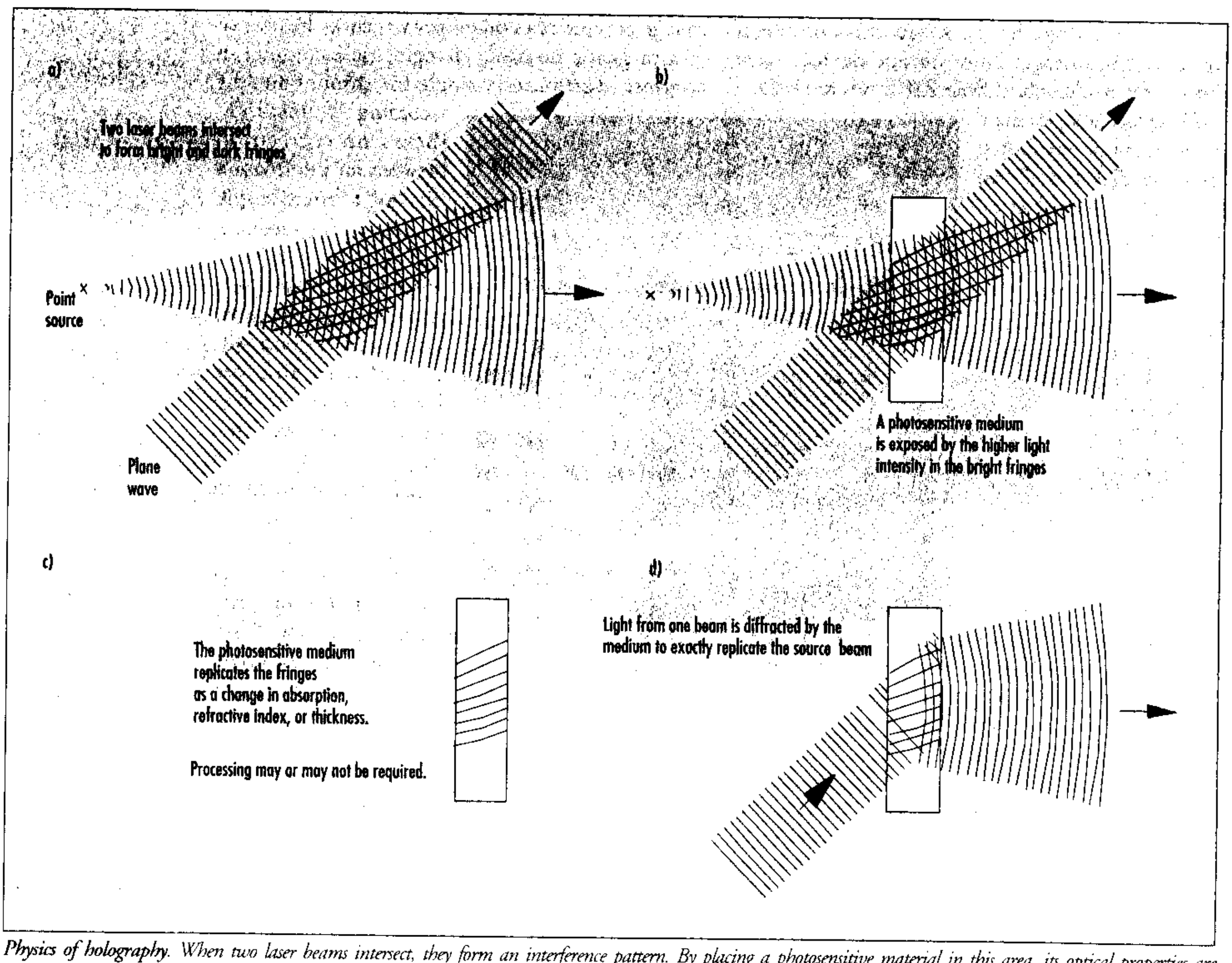
THE BRAGG EFFECT

Holographic storage can significantly increase areal density by using a thick layer to record multiple pages of data. A common misconception of holographic recording is that each page occupies a different depth in the recording volume. In reality, the holographic structures for multiple pages are mixed together, which is a process referred to as multiplexing. Meanwhile, the "Bragg effect" allows retrieving an individual page of data, while minimizing crosstalk from other pages—a feature of the highly tuned holographic structure. The diffraction efficiency varies according to mismatches in angle or wavelength between recording and playback. To attain 100% efficiency, an identical beam is used for both recording and playback. If, however, the illuminating beam is slightly off in direction or wavelength, the reconstruction efficiency will be less than 100%, falling to zero as this deviation increases, at which point another hologram can be recorded since it won't interact with existing holograms. At zero efficiency, the thicker the medium, the lower the mismatch angle. A controlled mismatch in the recording or playback angle of only a few thousandths of a degree allows many holograms to be recorded in the same volume. For example, multiple holograms can be stored in a 1.0-mm thick recording medium in angular increments of 0.025 degrees or wavelength increments of 9.5 nm.

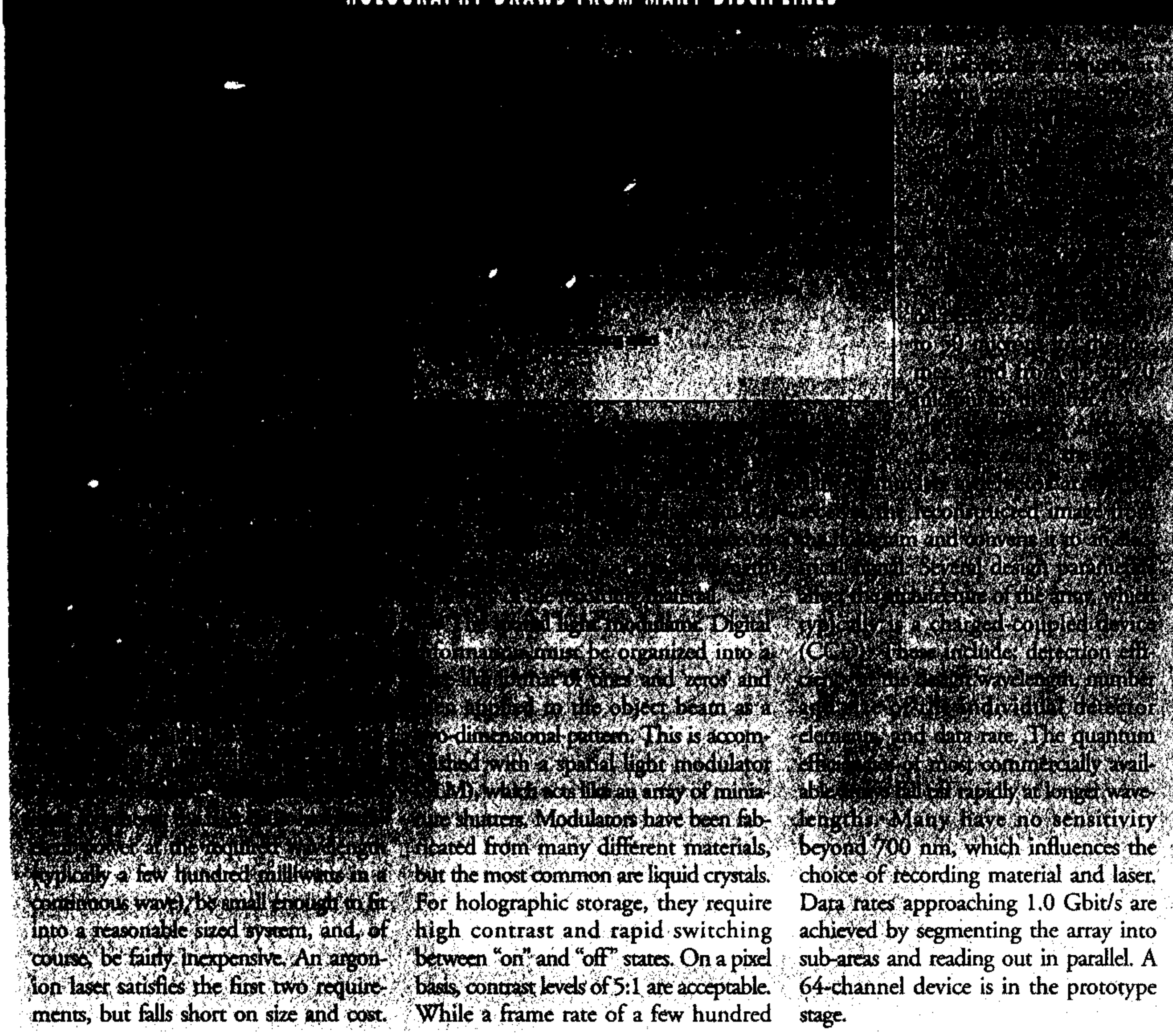
Using angular multiplexing, 10,000 holograms have been stored in one location of a 6-mm-thick lithium niobate crystal [1]. Angular multiplexing requires complex optics, making it more difficult to implement than wavelength multiplexing. However, wavelength multiplexing is highly dependent on the range over which lasers can be tuned. Today's tuning range reaches 20 nm at most, which is not wide enough to store many holograms simultaneously. Density can be improved with hybrid systems that combine angular and wavelength multiplexing, or that reposition the recording medium [2,3].

Another multiplexing technique, called "deterministic phase encoding", uses the phase of many reference beams to distinguish one hologram from another. Individual reference beams are simultaneously incident on the recording medium so that each hologram is recorded with a set of beams that differ only in phase. Altering the phase of the beams, rather than their direction, is a faster and potentially simpler process.

This multiplexing feature distinguishes holographic from conventional storage



Physics of holography. When two laser beams intersect, they form an interference pattern. By placing a photosensitive material in this area, its optical properties are changed so it mimics the interference pattern to form a hologram. Subsequent illumination of the hologram with one beam will recreate the pattern of the alternate beam.



[illegible] power at the required wavelength (typically a few hundred milliwatts in a continuous wave), be small enough to fit into a reasonable sized system, and, of course, be fairly inexpensive. An argon-ion laser satisfies the first two requirements, but falls short on size and cost.

[illegible] spatial light modulator. Digital information must be organized into a [illegible] of "ones" and "zeros" and [illegible] applied to the object beam as a two-dimensional pattern. This is accomplished with a spatial light modulator (SLM), which acts like an array of miniature shutters. Modulators have been fabricated from many different materials, but the most common are liquid crystals. For holographic storage, they require high contrast and rapid switching between "on" and "off" states. On a pixel basis, contrast levels of 5:1 are acceptable. While a frame rate of a few hundred

[illegible] the reconstructed image [illegible] and convert it to [illegible] signal. Several design parameters affect the architecture of the array, which typically is a charged-coupled device (CCD). These include: detection efficiency at the design wavelength, number [illegible] individual detector elements, and data rate. The quantum efficiencies of most commercially available [illegible] fall off rapidly at longer wavelengths. Many have no sensitivity beyond 700 nm, which influences the choice of recording material and laser. Data rates approaching 1.0 Gbit/s are achieved by segmenting the array into sub-areas and reading out in parallel. A 64-channel device is in the prototype stage.

methods. Two-dimensional storage allows data to be recorded and retrieved in parallel (a page at a time) rather than serially. Extremely high data rates are limited only by the I/O devices and electronic channels. For example, detector arrays available today run at giga-Hertz speeds by using multiple output taps, whereas massively parallel arrays can conceivably run at rates exceeding 1.0 GB/s.

Another distinguishing feature of holography is the speed at which data can be accessed. By relying on movement of light beams rather than a mechanical mass, access times of 10μs to 1 ms are achieved. True random access can be performed since it is not necessary to pass through other storage locations to reach a target location.

Latency is another factor that delays data in rotating storage systems, but which doesn't apply to holographic storage. Spatial and angular multiplexing also provides an opportunity to perform novel functions, such as "associative retrieval", in which holograms that are recorded at a given location are illuminated with a partial data page, rather than a particular reference beam. The complete data page that contains this partial input is then retrieved. Similar to pattern recognition, associative retrieval provides a very fast search mechanism, locating data by content rather than address.

The ideal material for holographic storage should be of high optical quality, with little scatter to insure that the signal-bearing wavefront doesn't become distorted and that the noise level from scattered light is manageable. It should be fairly thick (greater than 500 microns) to fully exploit the Bragg effect. A large refractive index change will insure that there is sufficient dynamic range to multiplex many holograms. The most common inorganic materials are ones that exhibit photo-refractivity, such as lithium niobate ($LiNbO_3$), strontium barium niobate (SBN), and barium titanate ($BaTiO_3$).

Lithium niobate has been available for many decades and can be fabricated in large crystals of high optical quality. The photorefractive effect occurs when the bright regions of the interference pattern excite electrons into the conduction band.

PHYSICS OF HOLOGRAPHY

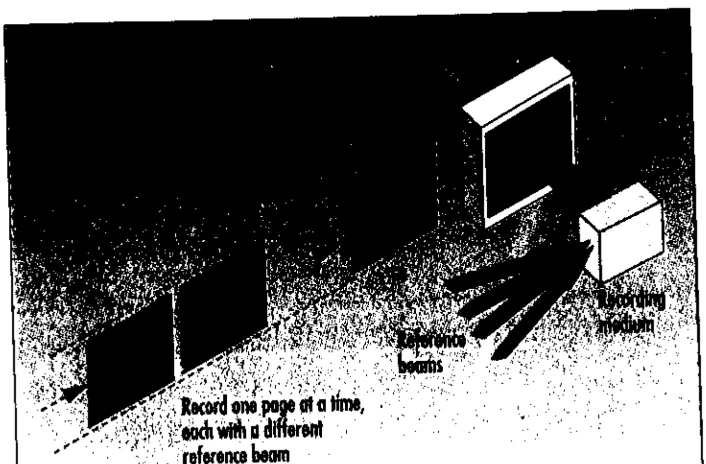
... pattern. If we now illuminate ... hologram with one of the original light beams, the structure in the hologram will diffract (bend) the light so it is identical to the other light beam used to form the interference pattern.

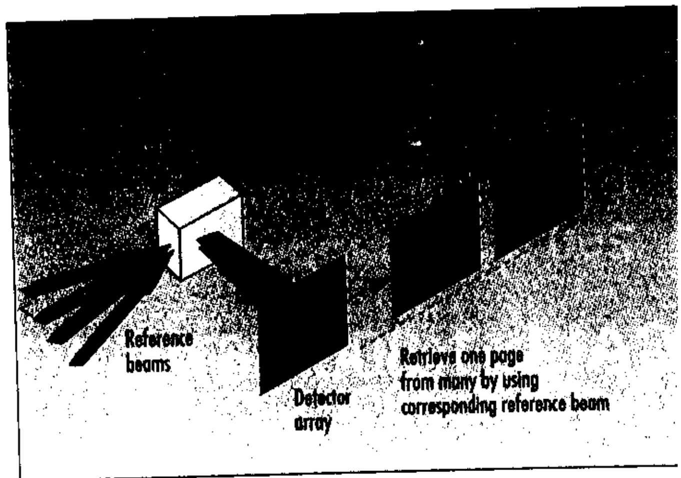
Materials store holographic images by changing an optical property in response to exposure to light.

The electrons subsequently drift into the dark regions and become trapped. The local fields that result interact with the host material to alter its index of refraction through an electro-optic effect. The resulting phase hologram can have up to 100% diffraction efficiency. Since these materials are made as thick as one centimeter, they can multiplex many holograms in the same volume. However, subsequent illumination, which occurs when additional holograms are recorded or when one is read, easily redistributes the electronic charge. Light from a second hologram rearranges some of the space charge field, partially erasing the first hologram. A third hologram exposure partially erases the first two. In effect, each hologram recorded partially erases all previously recorded holograms.

To counteract this affect, a recording schedule of decreasing exposure times is needed to equalize the diffraction efficiency of each hologram. An unwanted side effect is the efficiency of each hologram falls off as $1/N^2$ rather than $1/N$. This effect can be avoided by reducing the number of holograms in a common volume or by reducing the number of bits on a page. However, the number of photons per bit must be large enough so that the bit error rate does not increase to an unacceptable level. This is the major limiting factor in holographic storage capacity. And, unfortunately, this is not the whole story. The illumination required to read a single hologram partially erases the other holograms in that volume. Thus, holograms decay in efficiency with each reading until the bit error rate becomes unacceptable. The volatility of stored data requires a fixing process of some kind to render the holograms insensitive to subsequent illumination.

Thermal fixing is one such process whereby holograms are heated to around 120 C. The electronic space field charge interacts with ions, typically protons, that are more mobile at higher temperatures. Ions move to compensate for the charge differential and are locked in place when the temperature is reduced. Ionic charges reveal their own index variations when the readout illumination erases the electronic-space charge. This process works quite well, creating a permanent set of holograms with only a small loss in diffraction efficiency. However, there are some performance issues that need to be addressed with this method since it takes a long time to heat and cool the system. Thermal fixing is best suited for read-only applications where the holograms are recorded at a central facility and then distributed. If reasonable delays between recording and retrieving are allowed thermal fixing also may be suitable for write-once storage mode.





Holographic recording (left) involves transferring a two-dimensional pattern of "ones" and "zeros" to a spatial light modulator—which acts like an array of minature shutters. By passing a laser beam through the modulator, this data pattern interferes with a reference beam to form the hologram. Retrieving holographic data (right) is done by illuminating the recording medium with the reference beam to create pattern that is converted to an electrical signal.