홀로그램 저장 재료

Holographic materials

Material	Reusable	Processing	Type of hologram	Exposure (J/m2)	Spectral sensitivity	Resol. (lim./mm)	Max. diff. efficiency
Photographic emulsion	No	Wet chemical	Amplitude	5×10^{-3}	400-700	1000-10000	0.05
			Phase	5×10^{-3}			0.60
Dichromated gelatin	No	Wet chemical	Phase	10^2	350-580	>10000	0.90
Photoresists	No	Wet chemical	Phase	10^2	Uv-500	3000	0.30
Photopolymers	No	Post exposure	Phase	$10-10^4$	Uv-650	200-1500	0.90
Photochromics	Yes	None	Amplitude	10^2-10^3	300-700	>5000	0.02
Photothermo -plastics	Yes	Charge and heat	Phase	10^{-1}	400-650	500-1200 (bandpass)	0.30
Photorefractive							
LiNbO$_3$	Yes	None	Phase	10^4	350-500	>1500	0.20
Bi$_2$SiO$_{20}$	Yes	None	Phase	10	350-550	>10000	0.25

Holographic storage media parameters

- **Optical quality**

  For distortion-free imaging of the input data to the detector

  Storage medium is also one optical component

  Intrinsic light scattering: signal level minimum

- **Sensitivity**

  (Refractive index modulation) / (absorbed fluence)

- **Dynamic range (M/#)**

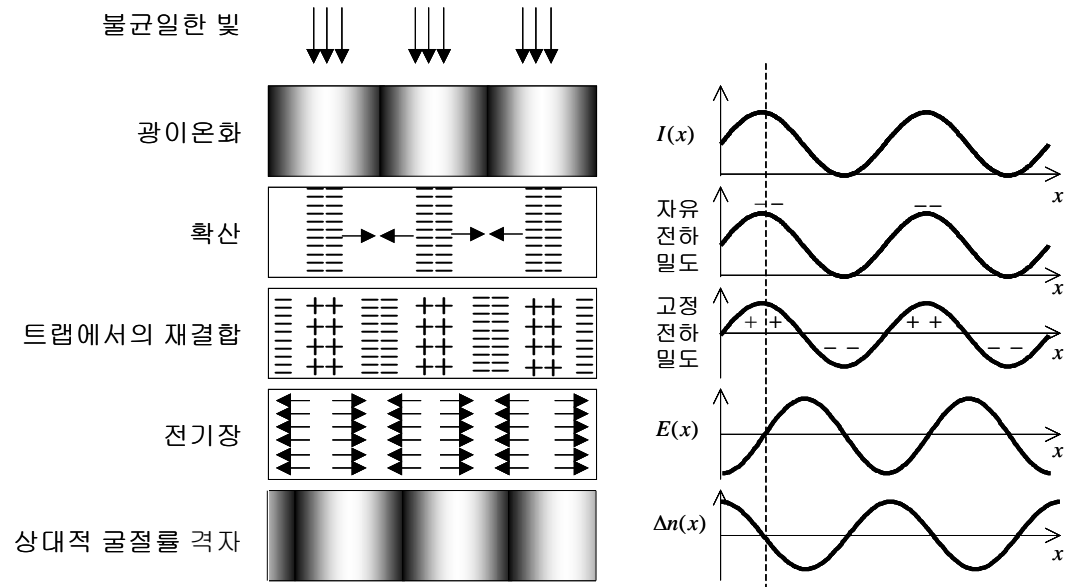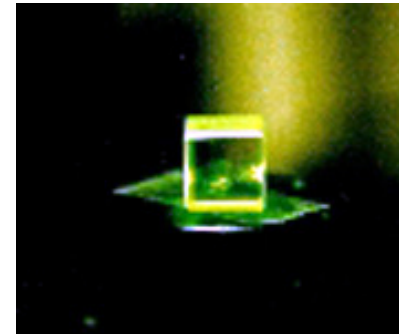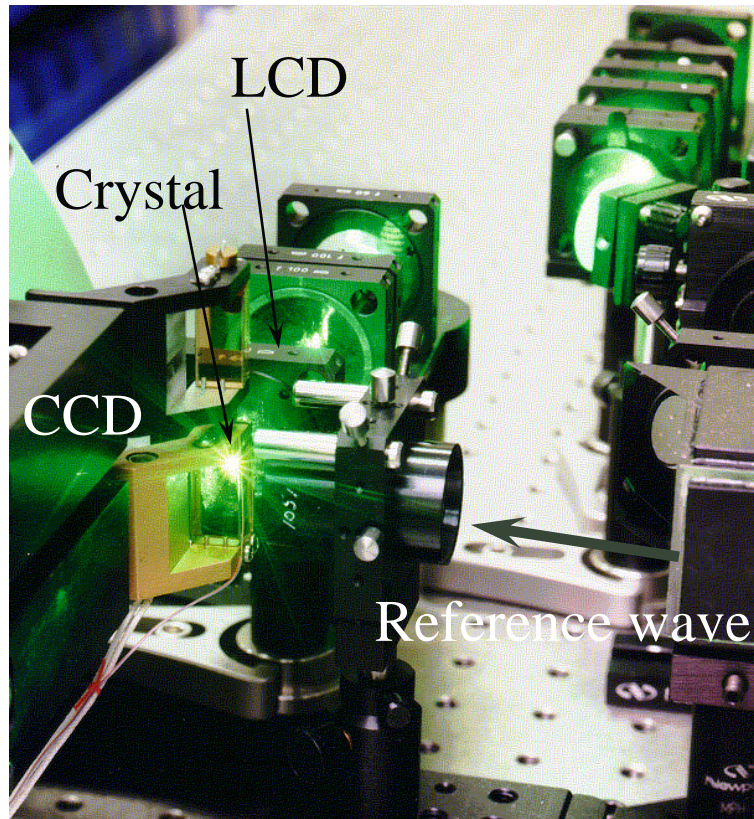 Total response of the medium divided among many multiplexed holograms
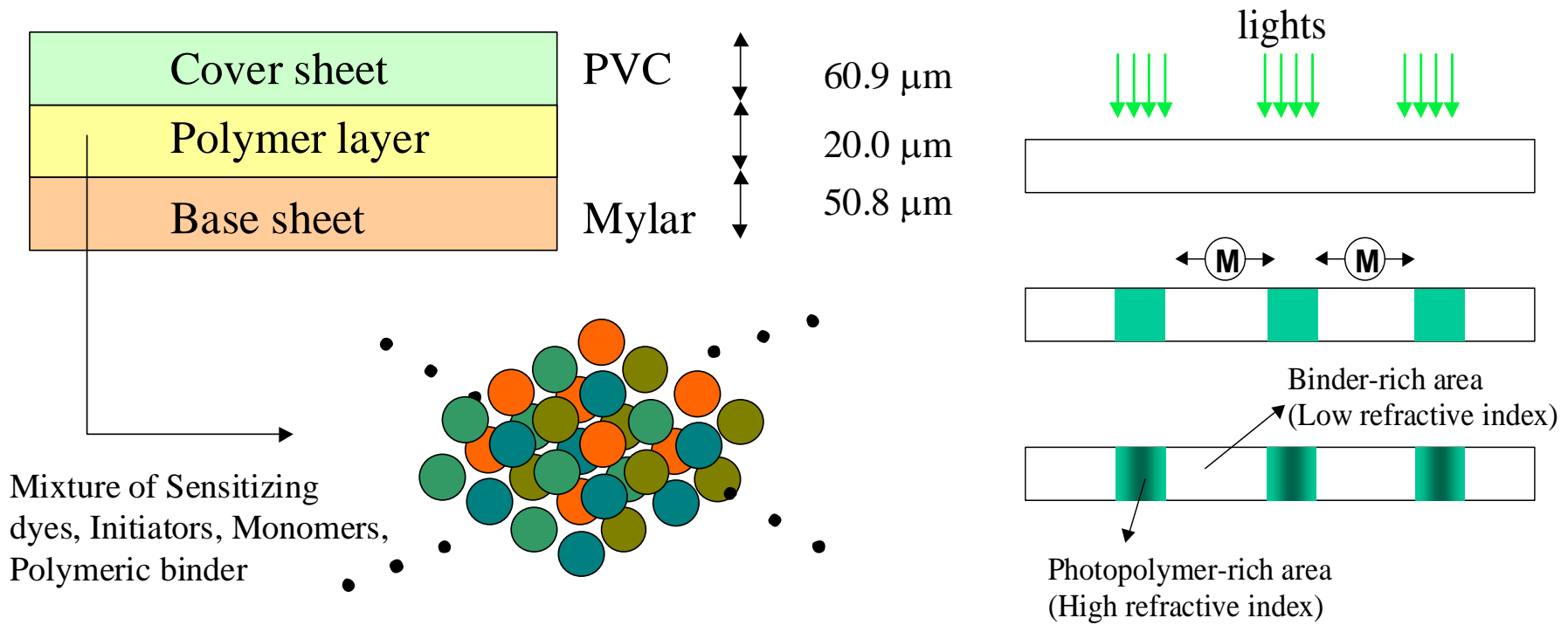
- **Absorption**

  Diffraction efficiency & selectivity

- **Volatility**

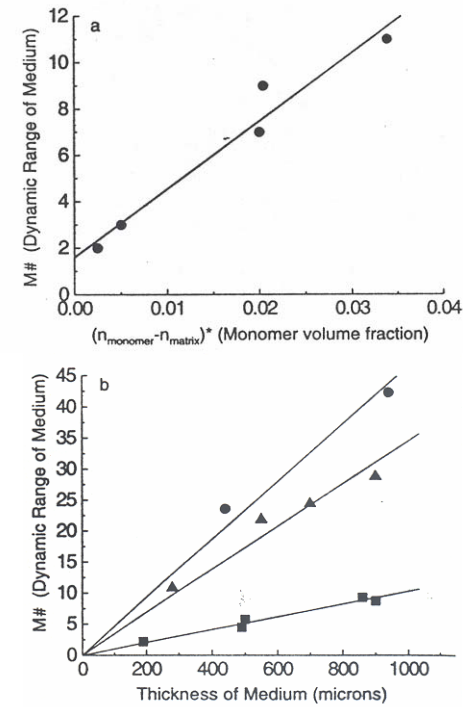 Dark decay (archival problem) and readout erasing

Photorefractive crystal

불균일한 빛

광이온화 $I(x)$

확산   자유 전하 밀도

트랩에서의 재결합   고정 전하 밀도

전기장 $E(x)$

상대적 굴절률 격자 $\Delta n(x)$

Photopolymer (1)

Cover sheet	PVC	60.9 μm
Polymer layer		20.0 μm
Base sheet	Mylar	50.8 μm

Mixture of Sensitizing dyes, Initiators, Monomers, Polymeric binder

lights

Binder-rich area
(Low refractive index)

Photopolymer-rich area
(High refractive index)

Photopolymer (2)
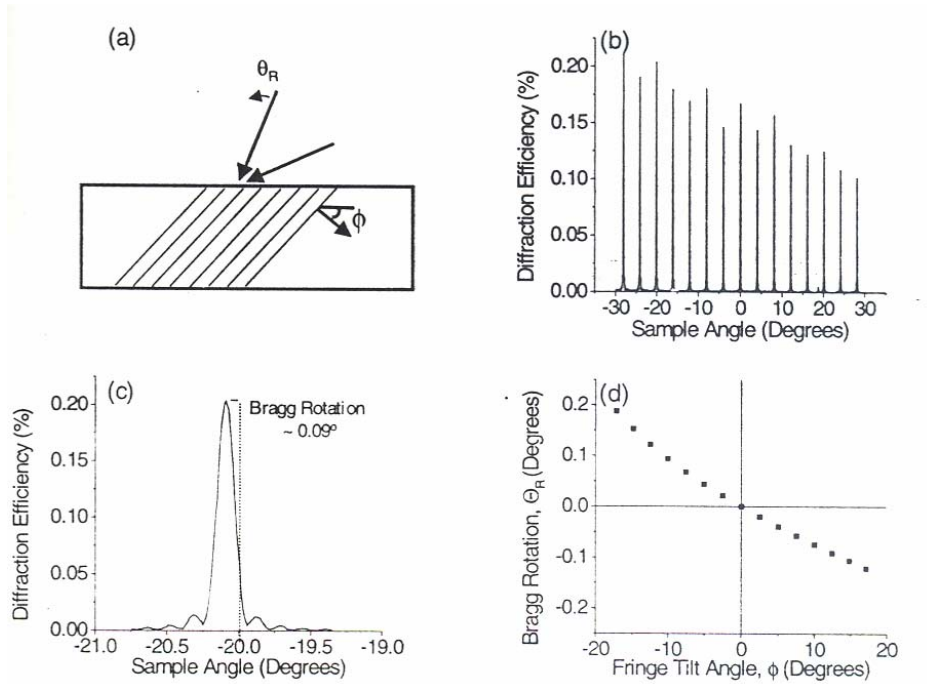
Shrinkage effect

Dynamic range

홀로그램 다중화

Multiplexing techniques
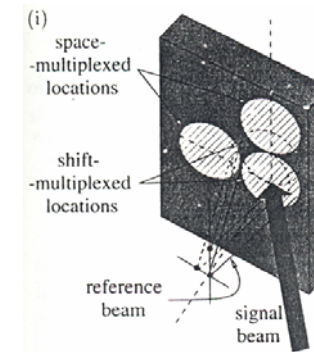

Angle multiplexing
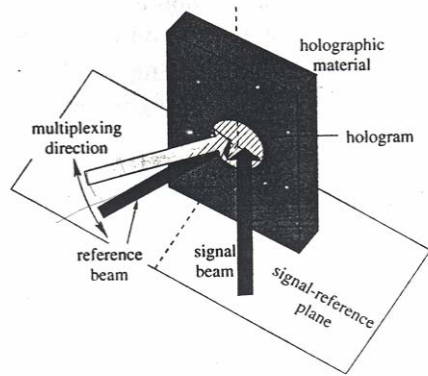
Wavelength multiplexing
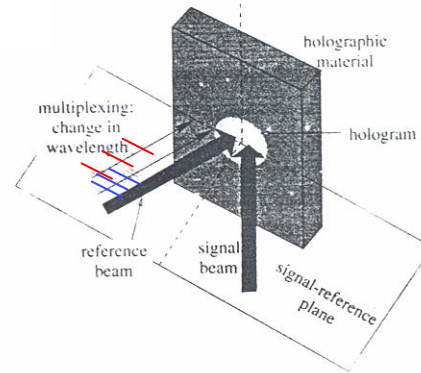
Spatial & angle multiplexing
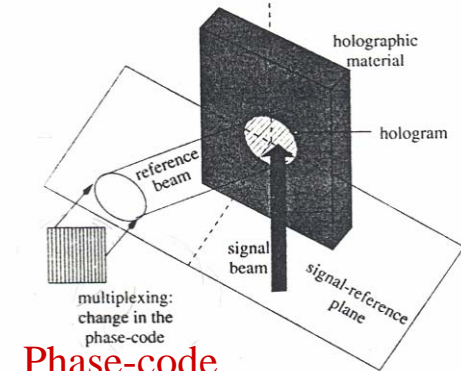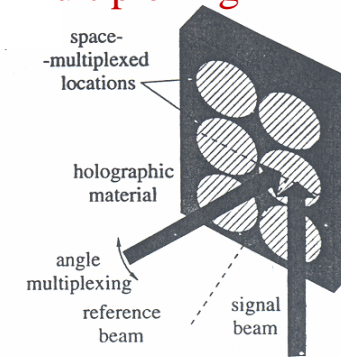
Phase-code multiplexing
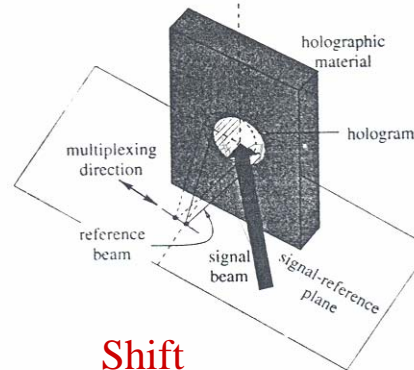
Shift multiplexing

Spatial & shift multiplexing
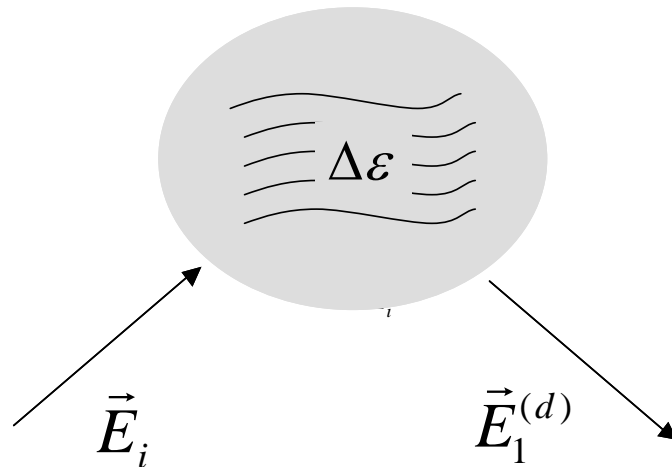
Hologram reading

Weak scattering of volume dielectric grating

$$\Delta\varepsilon$$

$$\vec{E}_i$$

$$\vec{E}_1^{(d)}$$

Holograms in HDS;

weak volume gratings $\qquad \Delta\varepsilon \propto R^* S$

1st Born approximation $\qquad S_d' \sim \Delta\varepsilon R_r' \sim SR^* R_r' \qquad$ *Correlation!*

Wave equation (vectorial, EM)

$$\varepsilon(\vec{r}) = \varepsilon_o + \tilde{\varepsilon}(\vec{r})e^{i\vec{K}_g \cdot \vec{r}}$$

$$\left(\nabla^2 + k^2\right)\vec{E} = U(\vec{r})\vec{E}$$

$$U(\vec{r}) = \frac{\tilde{\varepsilon}(\vec{r})}{\varepsilon_o} e^{i\vec{K}_g \cdot \vec{r}} \left\{ -i\vec{K}_g \times \vec{\nabla} + \vec{K}_g\left(\vec{K}_g \cdot\right) - k^2 \right\}$$

1st Born approx. (single scattering)

$$\vec{E}_i = e^{i\vec{k}_i \cdot \vec{r}}\hat{e}$$

$$\vec{E}_1^{(d)}(\vec{r}) = \vec{s}(\vec{k}_i)\int d^3 r' \frac{e^{i\vec{k}_i|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}\tilde{\varepsilon}(\vec{r}')e^{i(\vec{K}_g+\vec{k}_i)\vec{r}'}$$
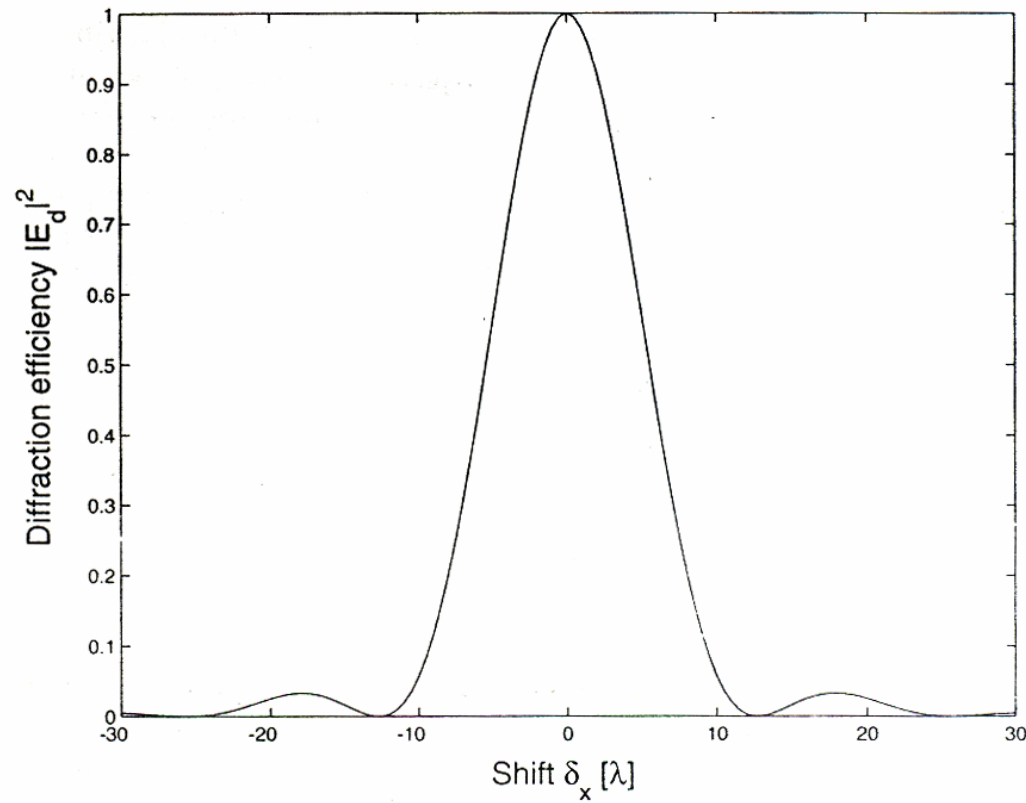
$$\vec{s}(\vec{k}_i) = \frac{\left(\vec{K}_g \cdot \hat{e}\right)\left(\vec{k}_i + \vec{K}_g\right) - k^2\hat{e}}{\varepsilon_o}$$

Selectivity

Multiplexing unit detune

Phase matching condition
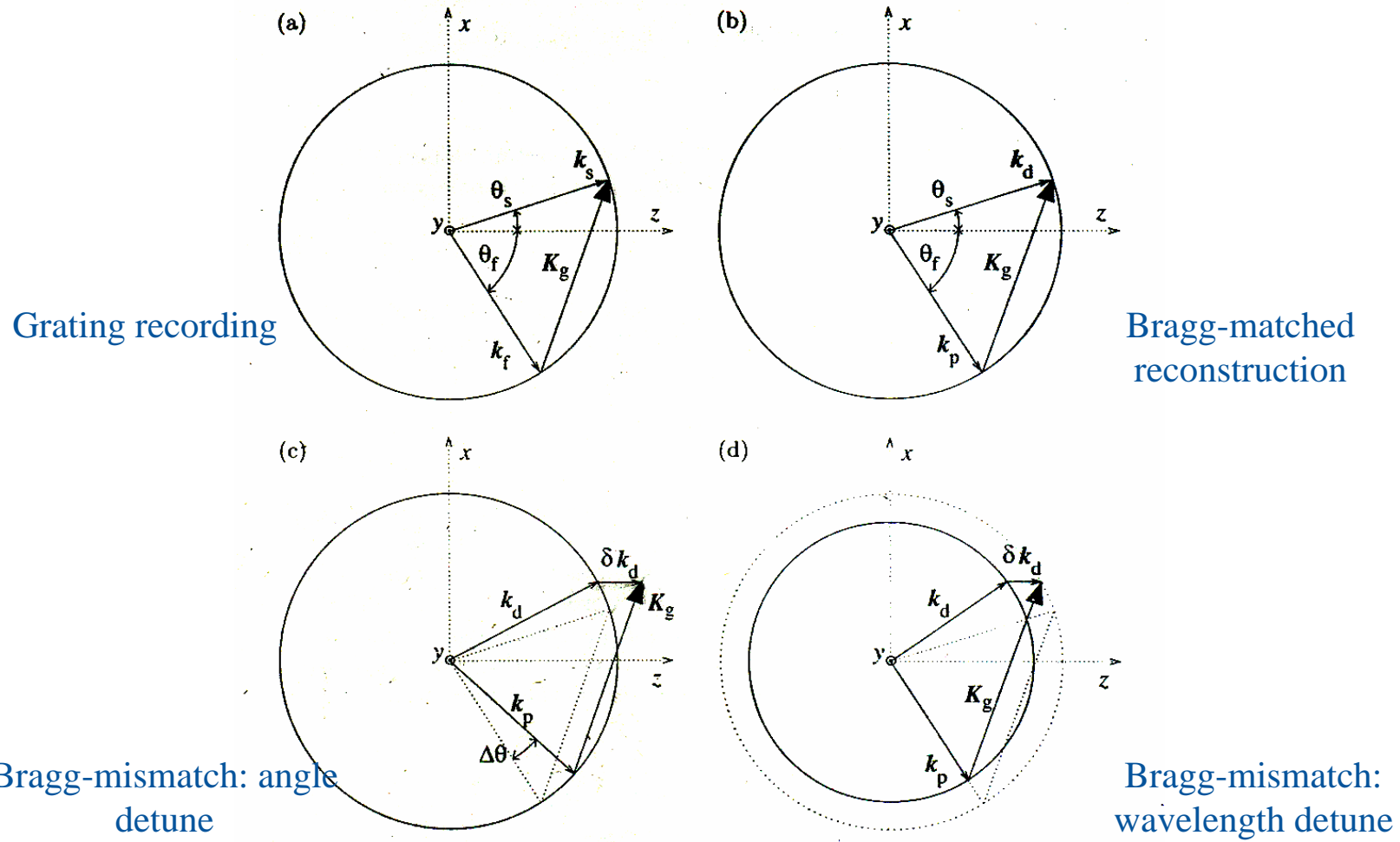
(a) Grating recording

(b) Bragg-matched reconstruction

(c) Bragg-mismatch: angle detune

(d) Bragg-mismatch: wavelength detune
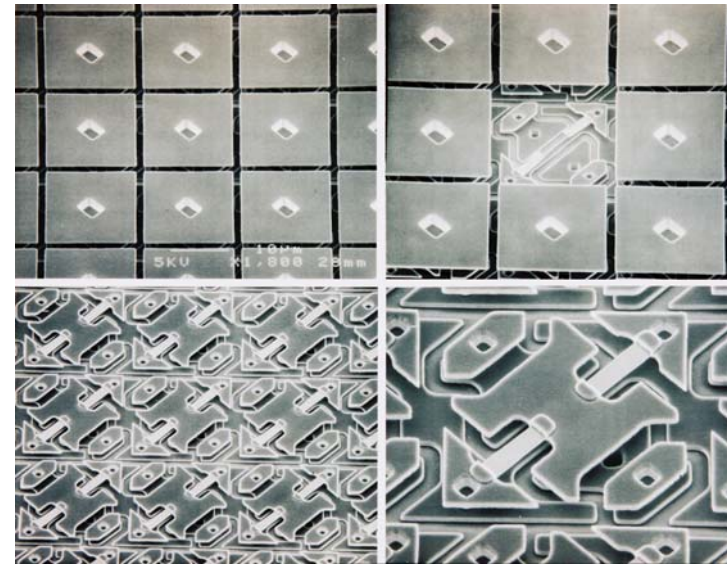
National Creative Research Center for Active Plasmonics Applications Systems

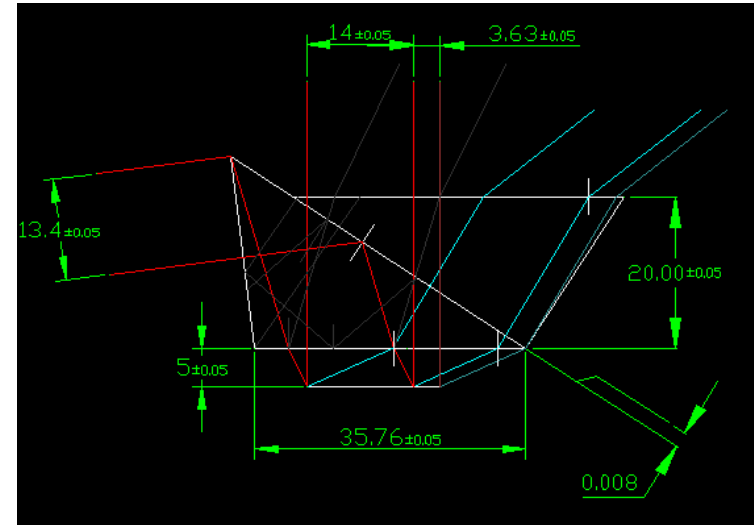# 공간광변조기

Spatial Light Modulator (SLM)
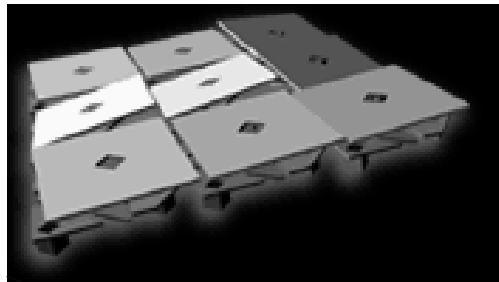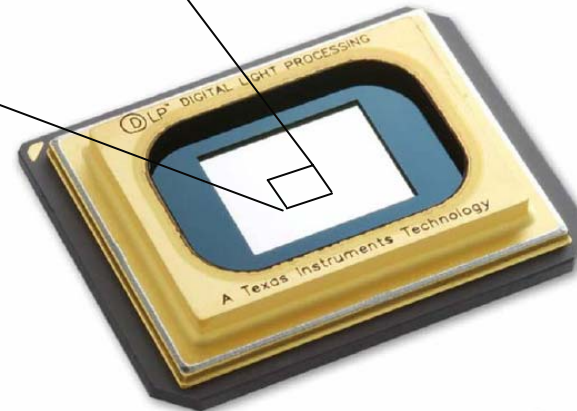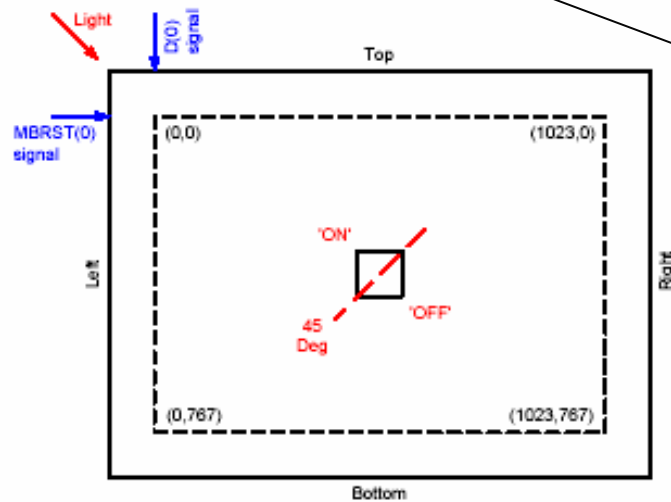

LCD modulator

Digital micromirror
modulator

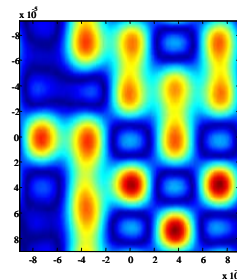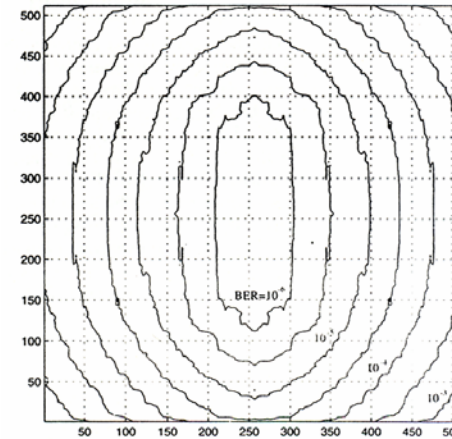# DMD의 구조 및 광학 구성

DMD structures

TIR prism for DMD

코딩

Coding

- **Modulation codes**
  - For binary detection;
    balanced block code…

- **Interleaving & ECC**
  - Reed-Solomon code (or convolutional code)
  - BER pattern => interleaving

- **Equalization**
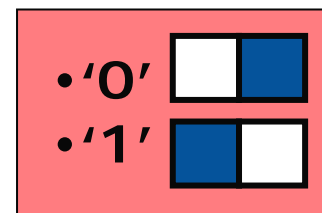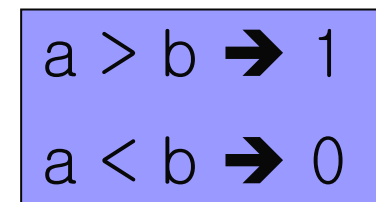 - ISI (inter-symbol interference) effect suppression
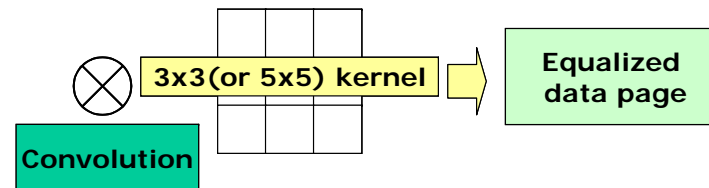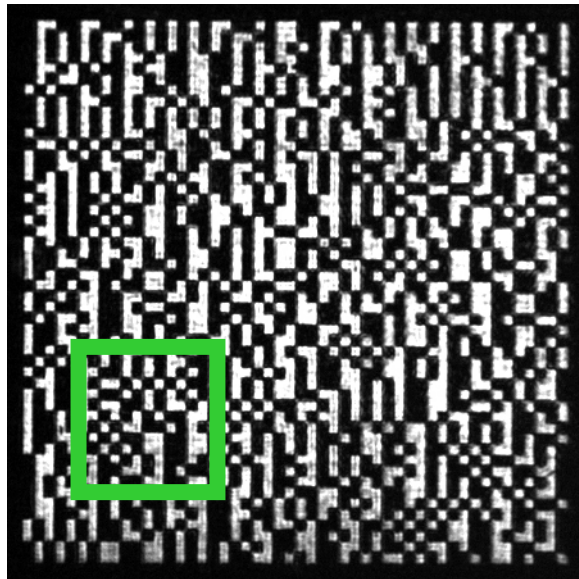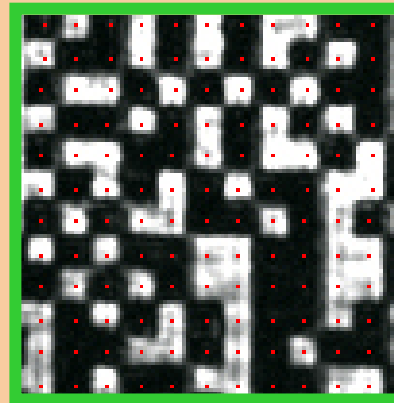
Modulation code

No modulation code

1:2 Modulation Code

'0' □■
'1' ■□
a b
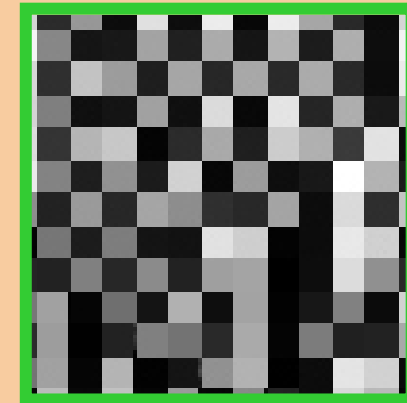
a > b ➜ 1
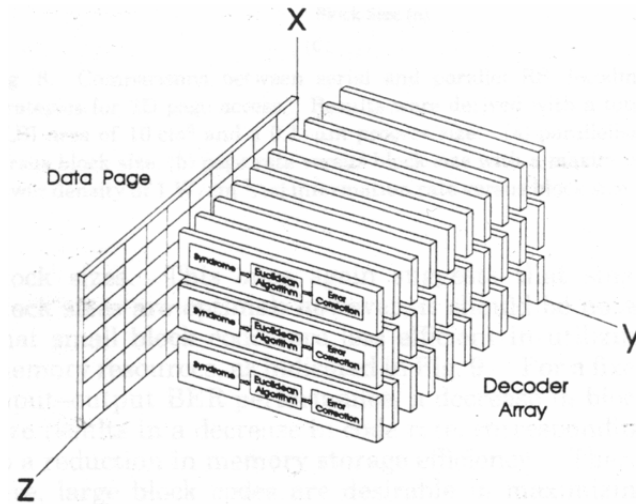a < b ➜ 0

Detection

Original image

Method 1:
Take the intensity of a sampling point (red point) of each block

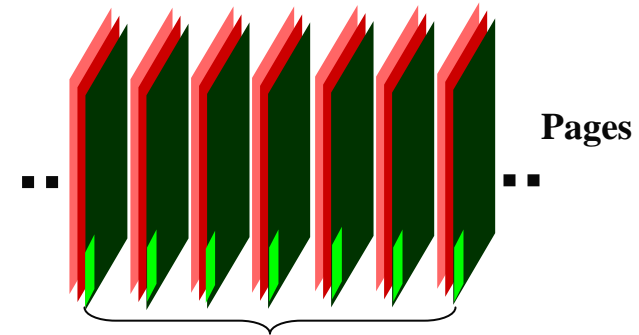Method 2:
Take the average of all intensities in each block
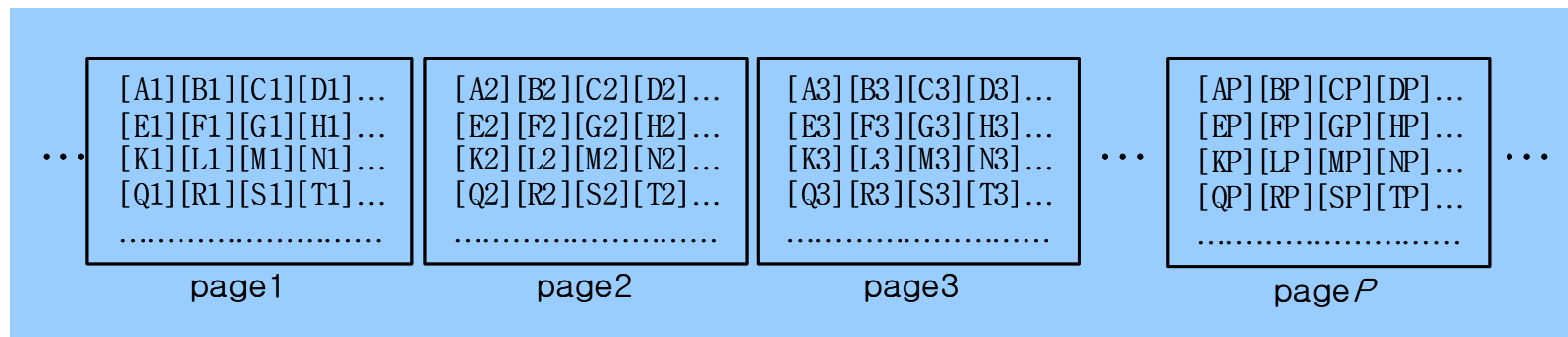
Array of code sequences
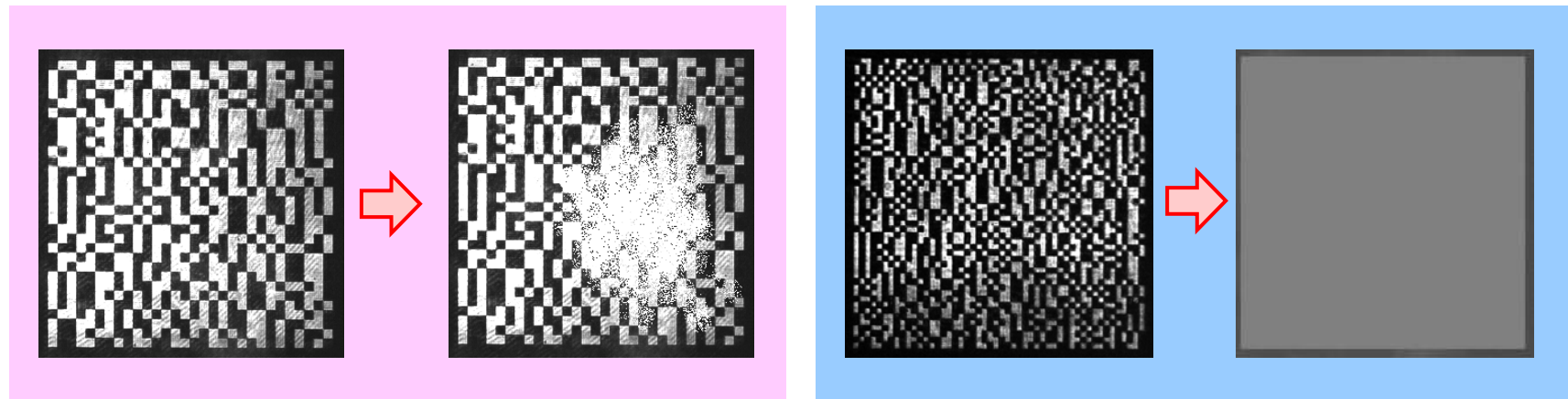

Two dimensional array of decoders

M.A Neifeld et al., Appl. Opt., **35**, 8183-8191 (1995).

Pages

Code sequence

Two dimensional array of code sequences

··· [A1][B1][C1][D1]…   [A2][B2][C2][D2]…   [A3][B3][C3][D3]…   ···   [AP][BP][CP][DP]… ···
     [E1][F1][G1][H1]…   [E2][F2][G2][H2]…   [E3][F3][G3][H3]…   [EP][FP][GP][HP]…
     [K1][L1][M1][N1]…   [K2][L2][M2][N2]…   [K3][L3][M3][N3]…   [KP][LP][MP][NP]…
     [Q1][R1][S1][T1]…   [Q2][R2][S2][T2]…   [Q3][R3][S3][T3]…   [QP][RP][SP][TP]…
     ………………..………   ………………..………   ………………..………   ………………..………

     page1   page2   page3   page P
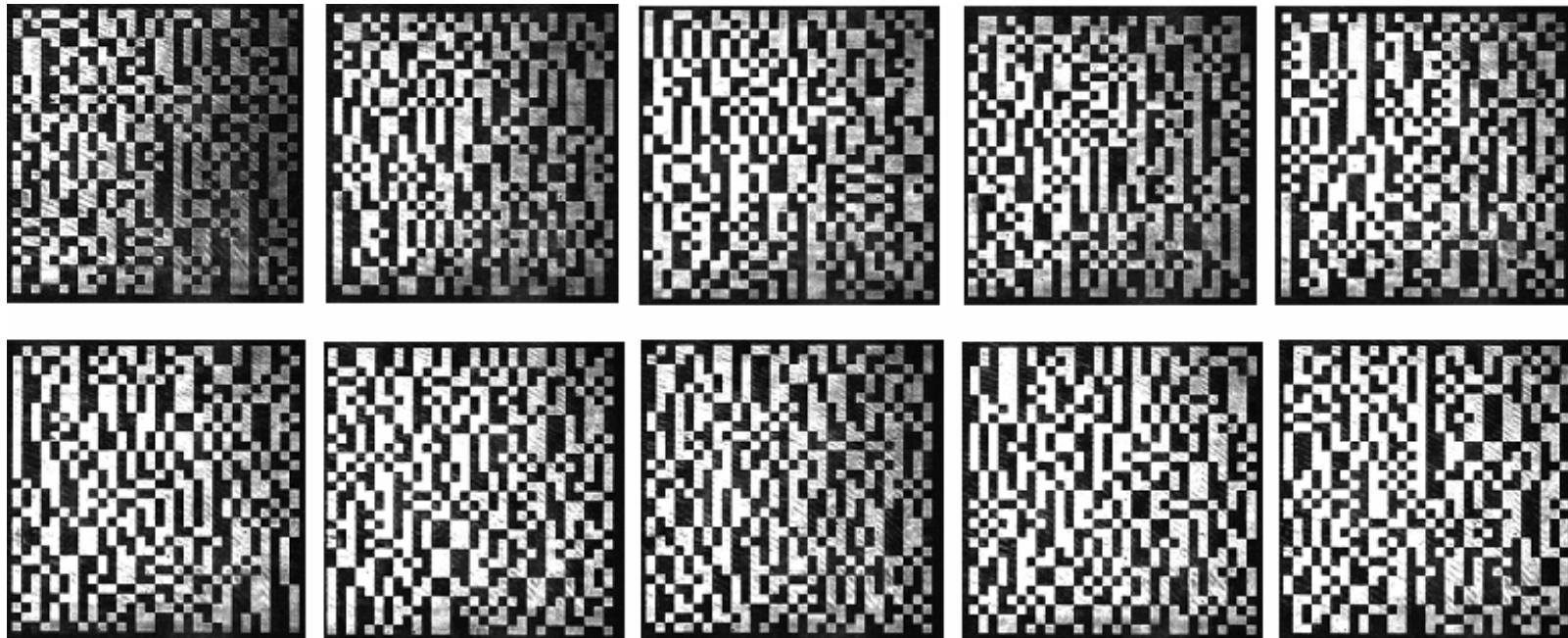
Burst error correction

- **Successful decoding is possible
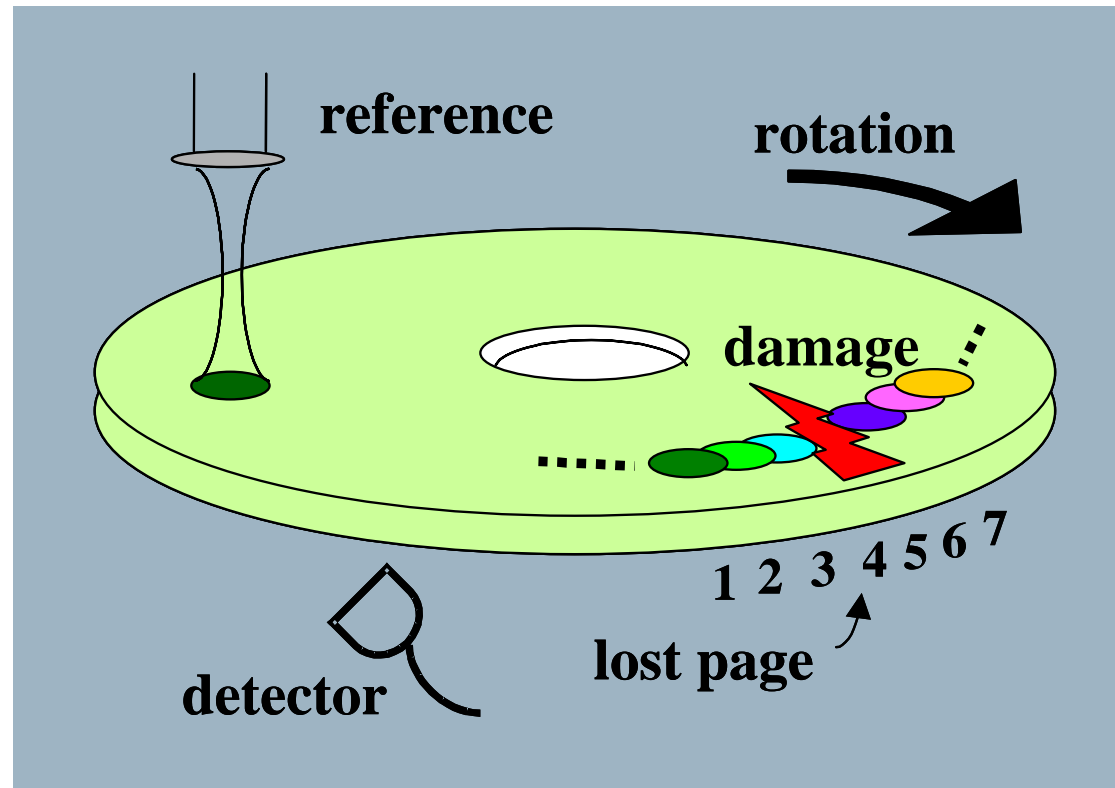 even if data pages are completely erased.**

Page Recovery

- **Without 10 pages**
    - 2, 10, 19, 23, 30, 36, 48, 49, 58, 68

- **(7,4) Hamming code**

Example of burst error

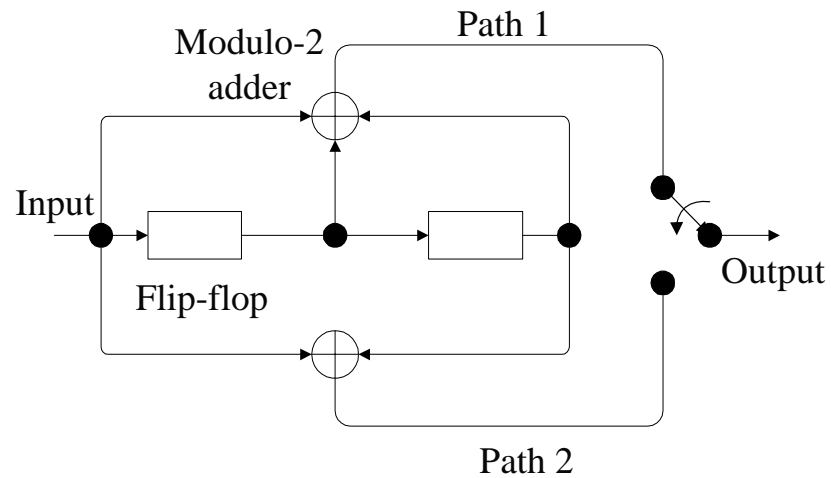# Convolutional codes

- Error correction codes

    Block codes – BCH, RS

    Convolutional codes

- Soft decision decoding

    Extra coding gain

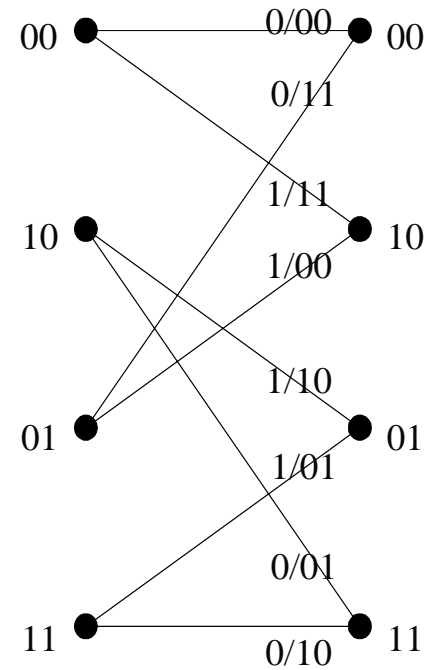- Viterbi algorithm

Encoder (convolutional code)

- **Encoder**
- **(n = 2, k = 1, m = 2)**
- **g = (7, 5)**

- Trellis diagram

Soft decision decoding in Viterbi algorithm

- **Quantization of received signal into Q levels**
  - Q = infinite : ideal soft decision
  - Q = 2 : hard decision
  - Q = 8 : practically good enough

- **3 bits/sample A/D conversion of received signal makes 2dB extra coding gain at BER=10^{-5} compared to hard decision.**
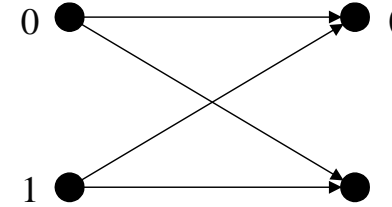
- **Little increase of decoder complexity**

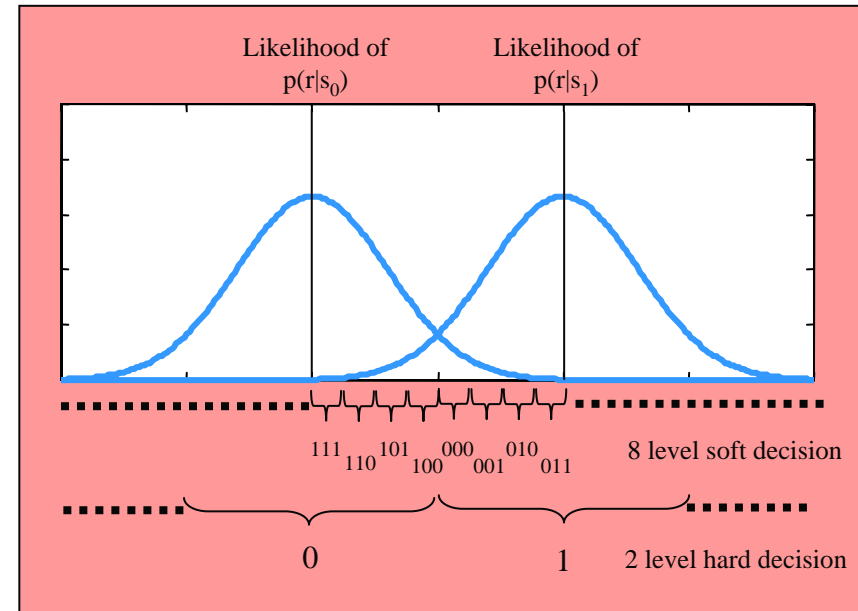# Soft decision decoding
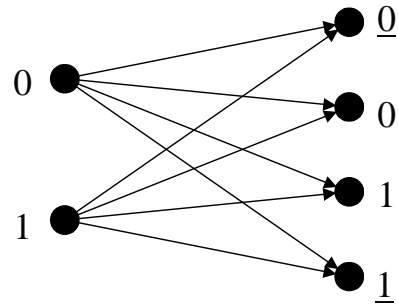
• Soft decision (Q=8)
  Discrete channel model
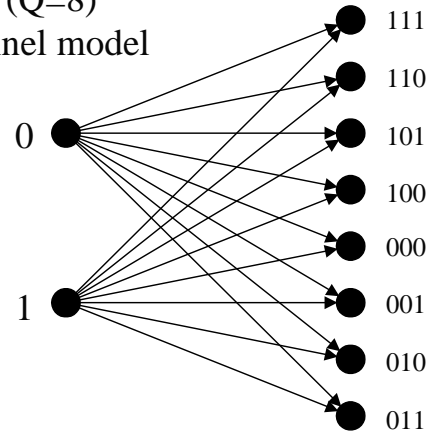
• Hard decision (Q=2)
  Binary channel model

Signal	Hard decision data	Sign-magnitude representation
Most negative		111
	0	110
		101
Least negative		100
Least positive		000
	1	001
		010
Most positive		011

Soft decision decoding

Discrete channel model (Q=4)

Received symbol	0	1
0	0.50	0.05
0	0.32	0.13
1	0.13	0.32
1	0.05	0.50

Conditional Probabilities

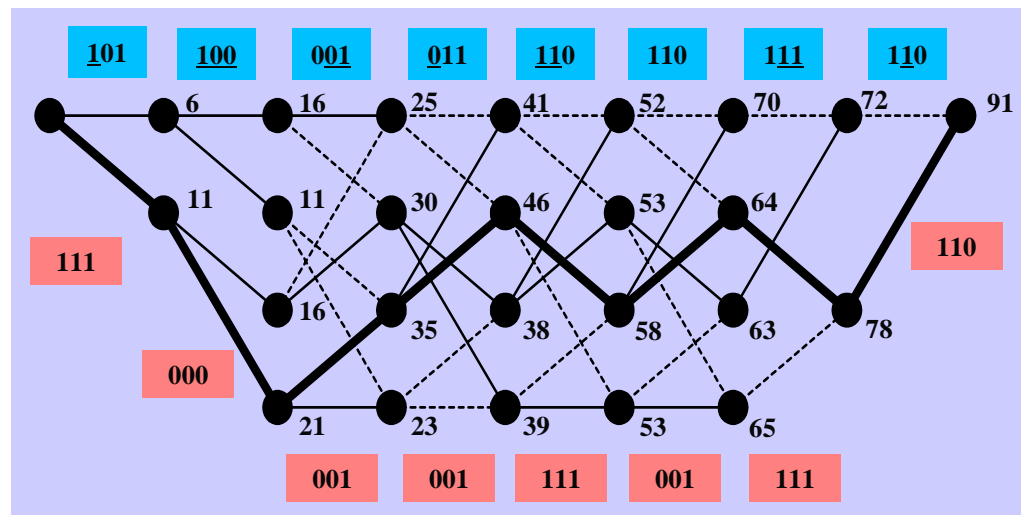| Received symbol	0	1
0	5	0
0	4	2
1	2	4
1	0	5

Bit metrics
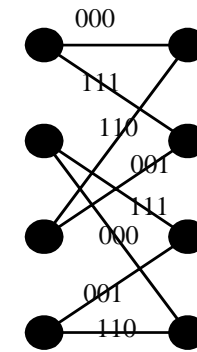
Trellis

- **Soft decision decoding for an (1, 3) code**

Transmitted
(111,000,001,001,111,001,111,110)

Received
(101,100,001,011,110,110,111,110)

Decoded
(111,000,001,001,111,001,111,110)

Experiment – Soft Decision Decoding
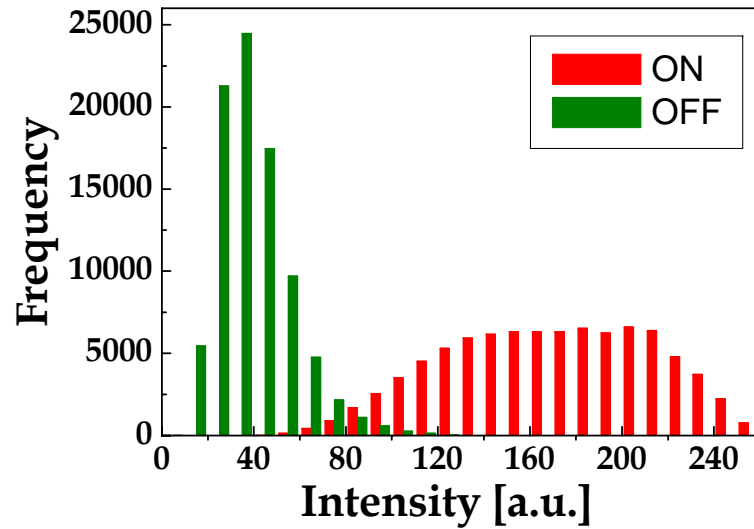
Quantization level	BER
Q=2	0.03~0.08
Q=4	0.006~0.022
Q=8	0.005~0.017

Received symbol	Interval	0	1
0	-INF 120	0.87	0.11
1	121 +INF	0.13	0.89

Q=2

Received symbol	Interval	0	1
11	-INF 110	0.750	0.075
10	111 130	0.190	0.060
00	131 150	0.054	0.060
10	151 +INF	0.006	0.805

Q=4

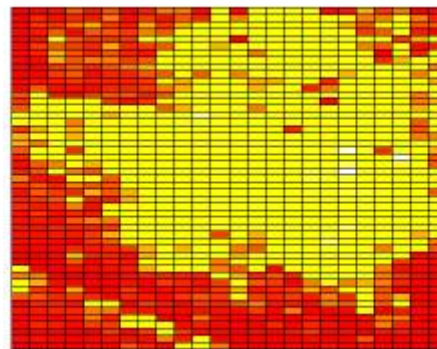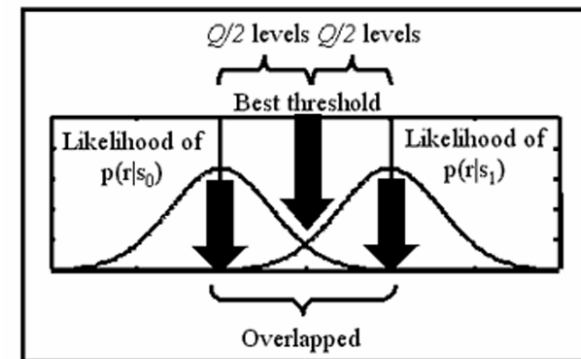| Received symbol	Interval	0	1
111	-INF 100	0.600	0.040
110	101 110	0.150	0.035
101	111 120	0.120	0.030
100	121 130	0.070	0.030
000	131 140	0.040	0.030
001	141 150	0.014	0.030
010	151 160	0.005	0.035
011	161 +INF	0.001	0.770

Q=8

Intrapage intensity variations
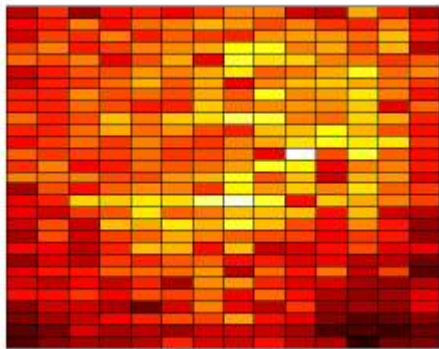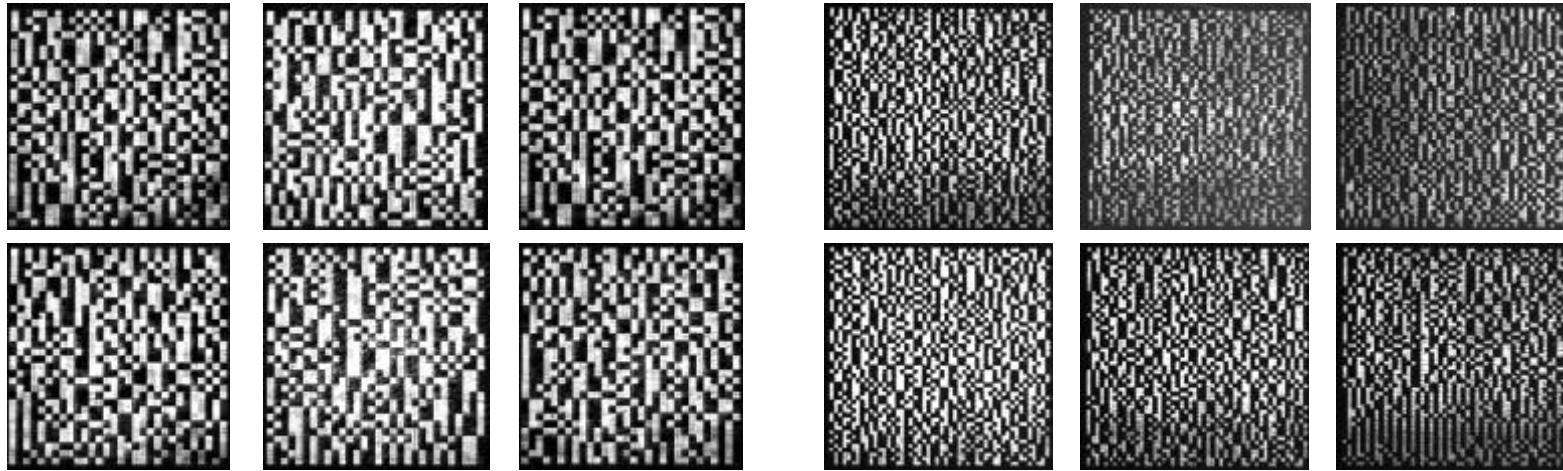
Best thresholds for 52 pages
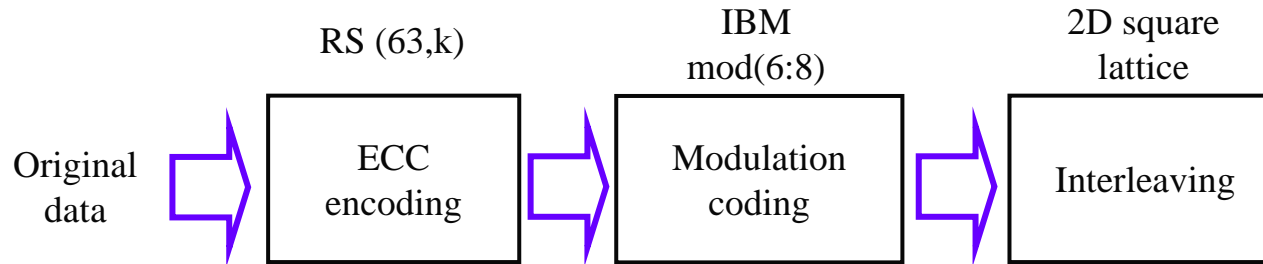with 30x30 blocks
(1.3 inch diagonal SLM)

Best thresholds for 70 pages
with 50x50 blocks
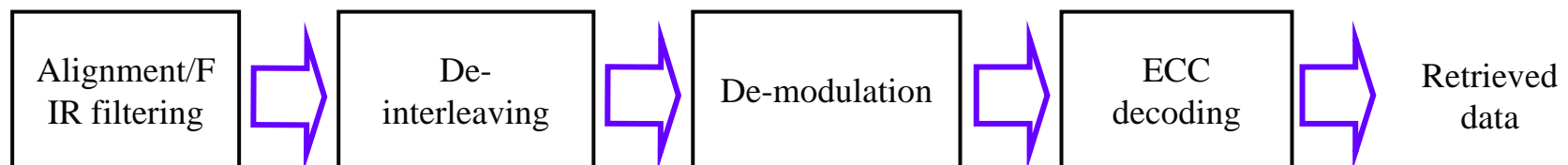(0.24 inch diagonal SLM)

Sequence of Coding

Generating pages

RS (63,k)   IBM mod(6:8)   2D square lattice

Original data ⟹ | ECC encoding | ⟹ | Modulation coding | ⟹ | Interleaving |

Record/reconstruction

| Simulation : shift, Illumination, rotation, oversampling | OR | Experiment :LGE |

Retrieving data

| Alignment/F IR filtering | ⟹ | De-interleaving | ⟹ | De-modulation | ⟹ | ECC decoding | ⟹ Retrieved data

Examples

Page generation condition
Page size: 512x384
RS ECC: (63,51)

Simulation condition
Rotation: 0.2(rad)
Shift: (0.2,0.3)(pixels)
Illumination: 0.8:1
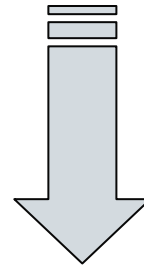
Simulation
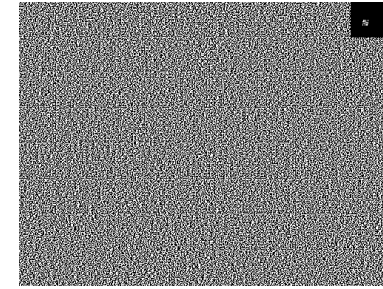
(1of 10)

(1of 10)
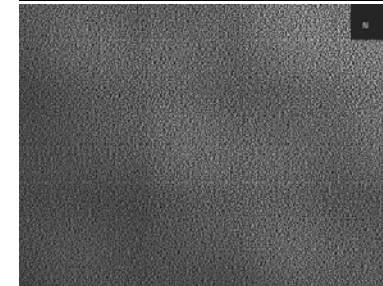
(1of 10)
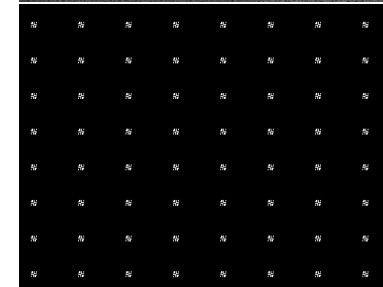
(1of 10)

시스템 설계

Holographic Data Storage System (I)
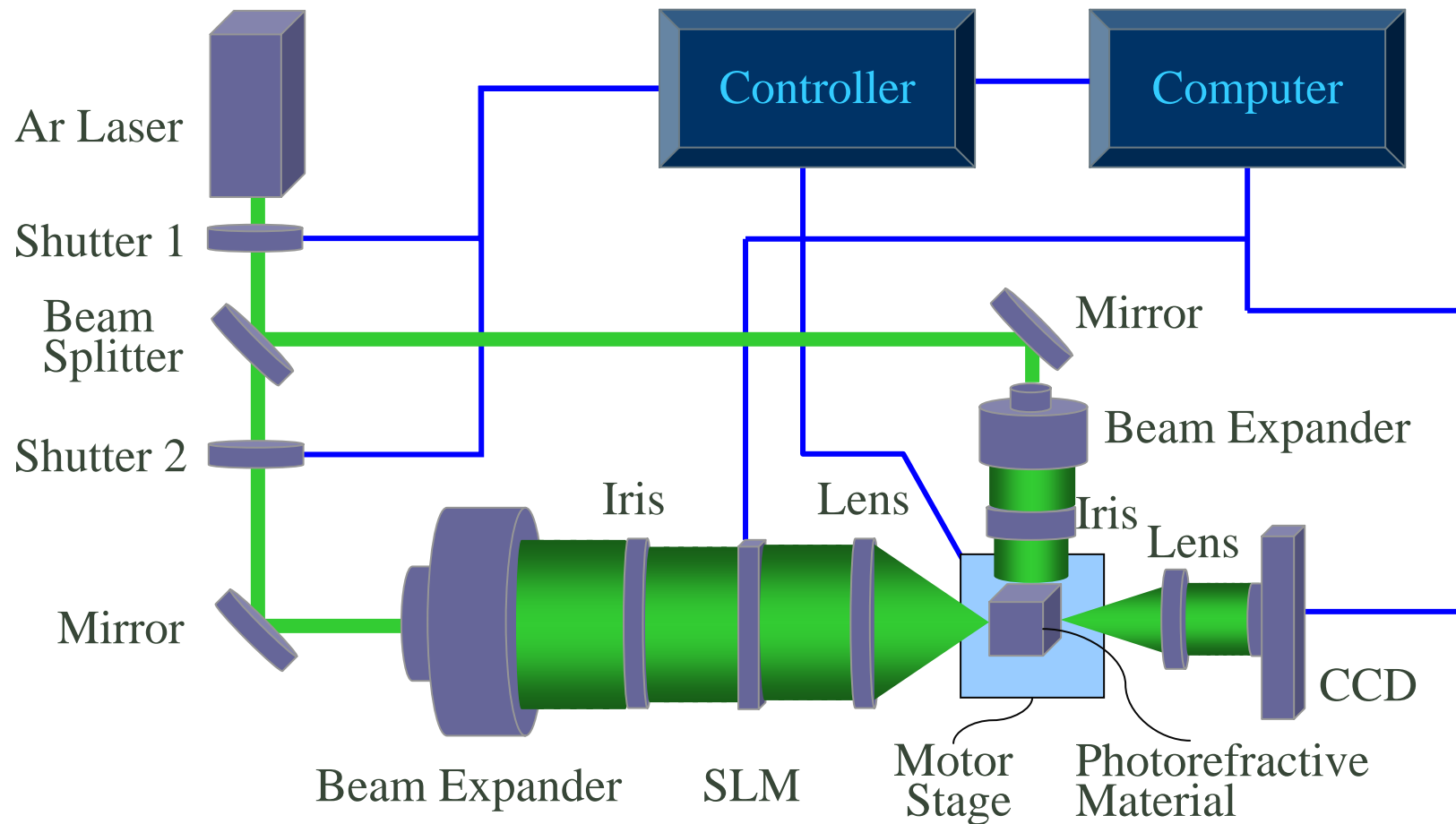
HDS system (II)
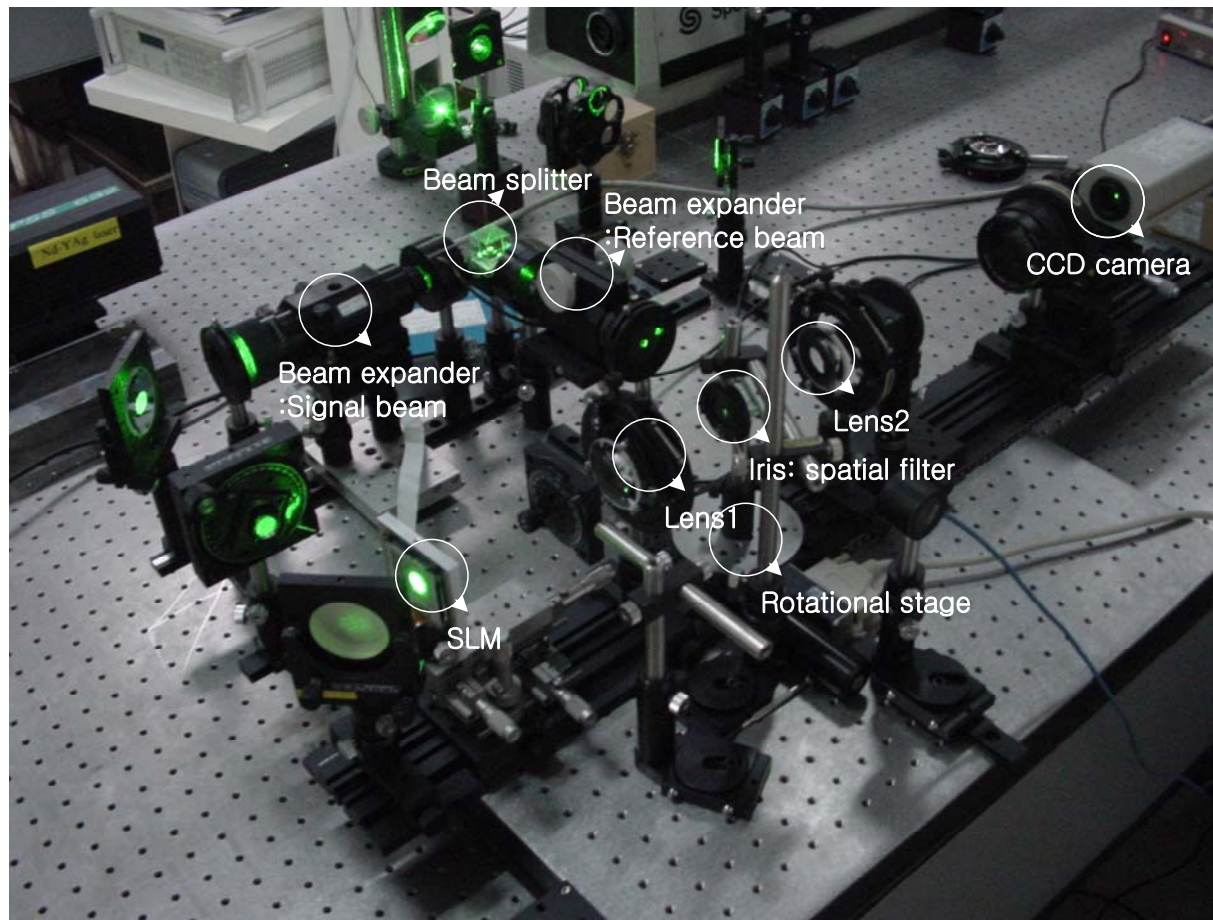
Exposure Schedule

$$A = A_0 \left[1 - \exp\left(-\frac{t_r}{\tau_r} \right) \right]$$
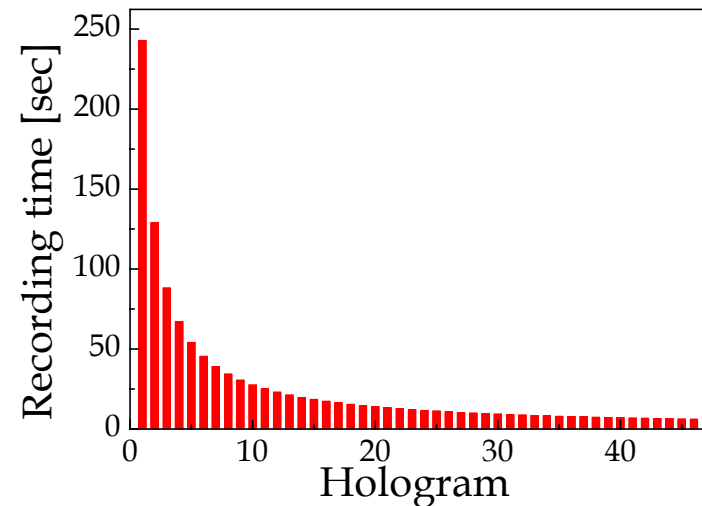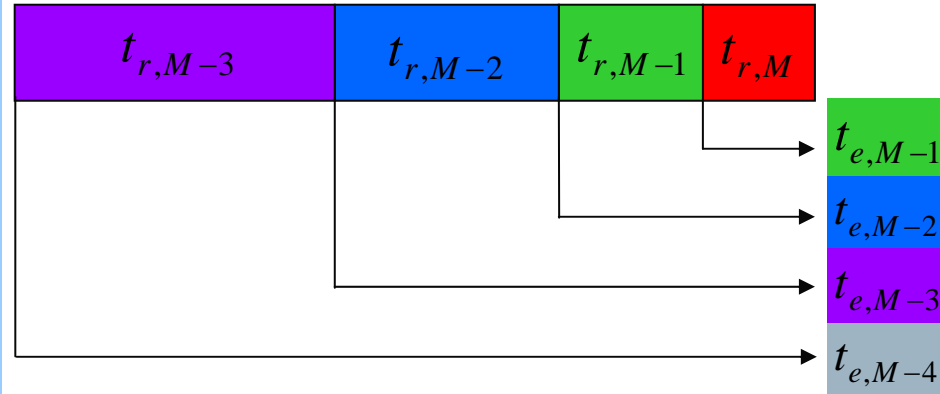
$$A' = A \exp\left(-\frac{t_e}{\tau_e} \right)$$

$$A'' = A_0 \left[1 - \exp\left(-\frac{t_r}{\tau_r} \right) \right] \exp\left(-\frac{t_e}{\tau_e} \right)$$

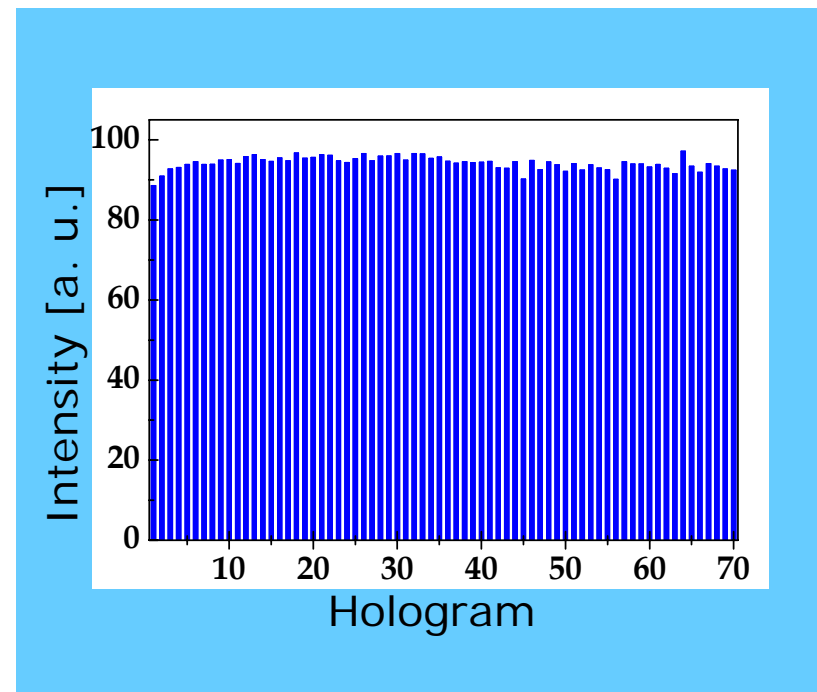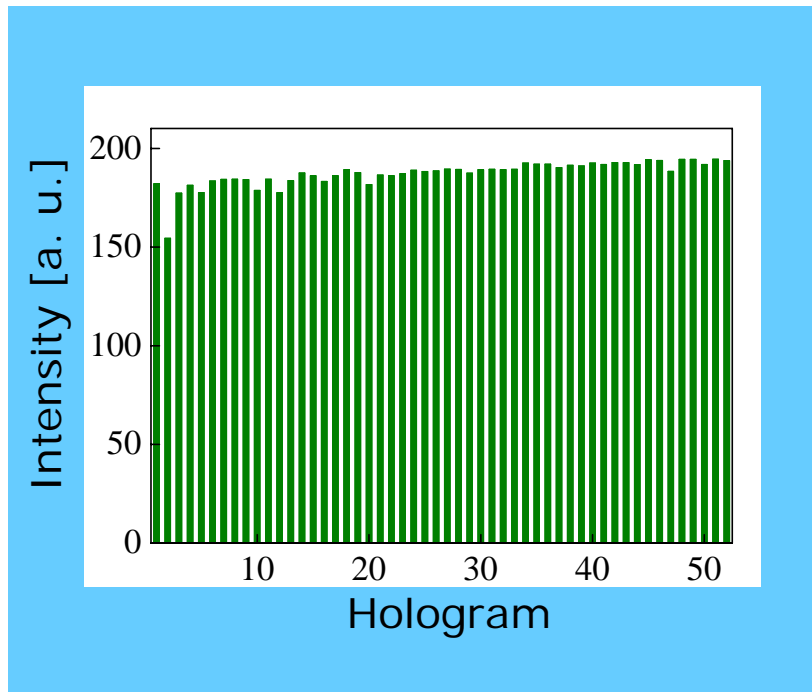$$t_r(t_e) = -\tau_r \ln\left[1 - \frac{A''}{A_0} \exp\left(\frac{t_e}{\tau_e} \right) \right]$$

$$t_{e,n} = \sum_{k=n+1}^{M} t_{r,k}$$
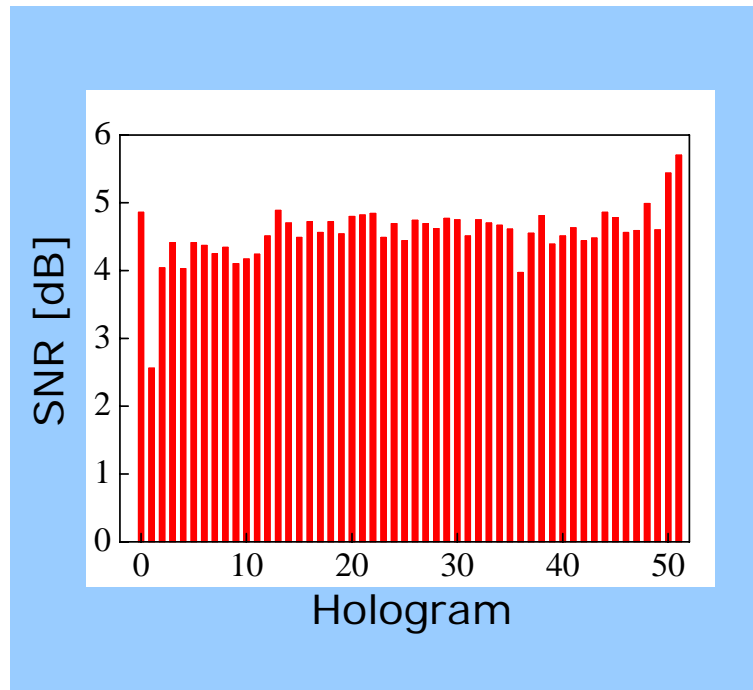
$$t_{r,n} = t_r(t_{e,n})$$
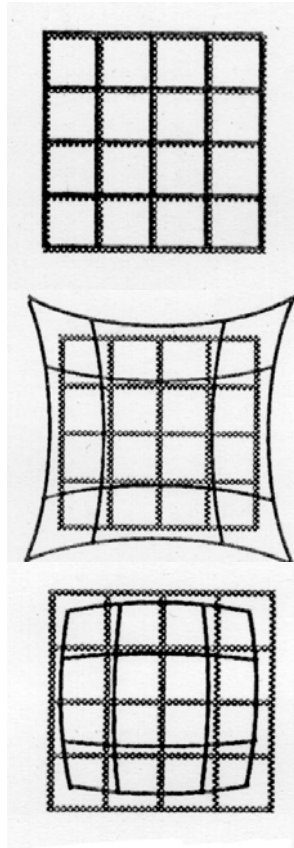
Recording time

Diffraction efficiencies

SNR

$$\text{SNR} = \frac{m_1 - m_0}{\sqrt{\sigma_1^2 + \sigma_0^2}}$$

- m_1: mean of on-bit intensities
- m_0: mean of off-bit intensities
- σ_1^2: variance of on-bit intensities
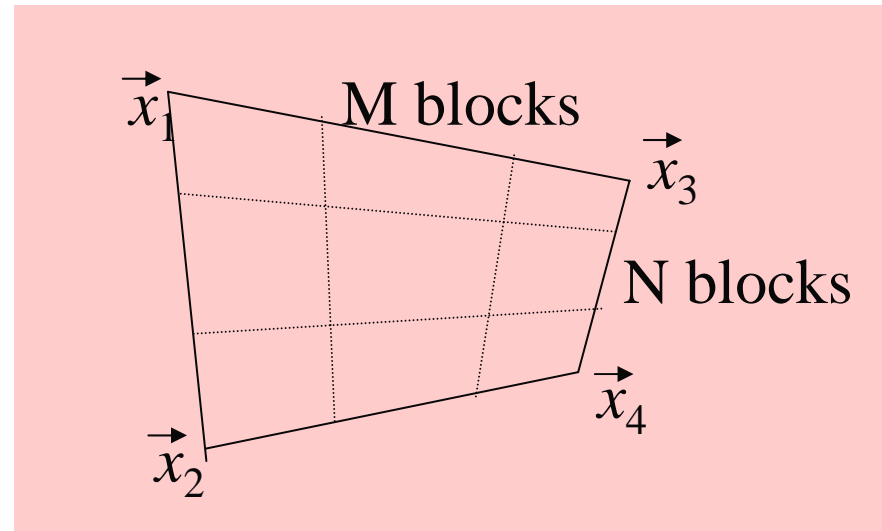- σ_0^2: variance of off-bit intensities

Image distortion detection (1)

Zero
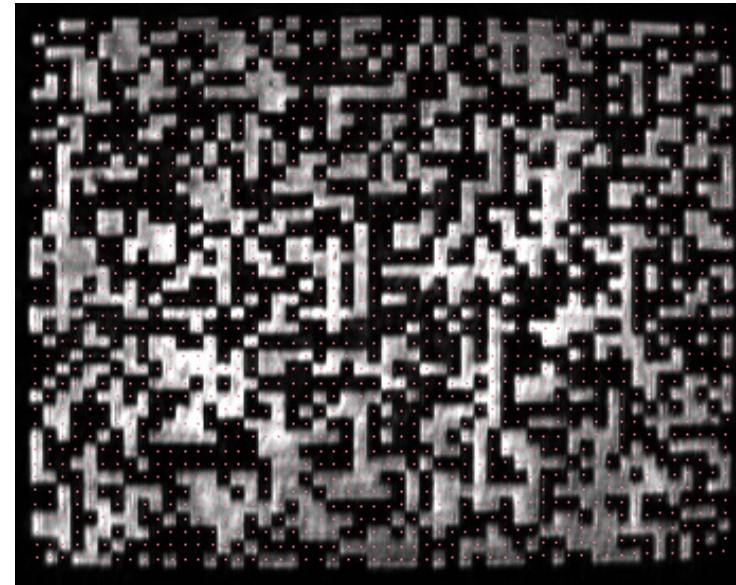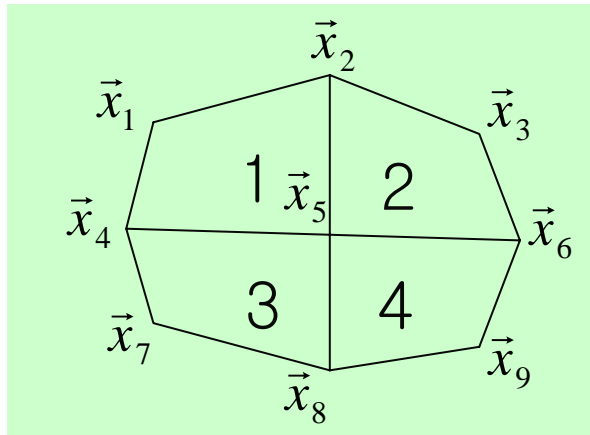distortion

Pincushion
(or positive)
distortion

Barrel
(or negative)
distortion

$$\frac{1}{4}[\vec{x}_1(2-\frac{2n+1}{N})+\vec{x}_2(\frac{2n+1}{N})](2-\frac{2m+1}{M})$$
$$+\frac{1}{4}[\vec{x}_3(2-\frac{2n+1}{N})+\vec{x}_4(\frac{2n+1}{N})](\frac{2m+1}{M})$$

Image distortion detection (2)

- ## Imaging system

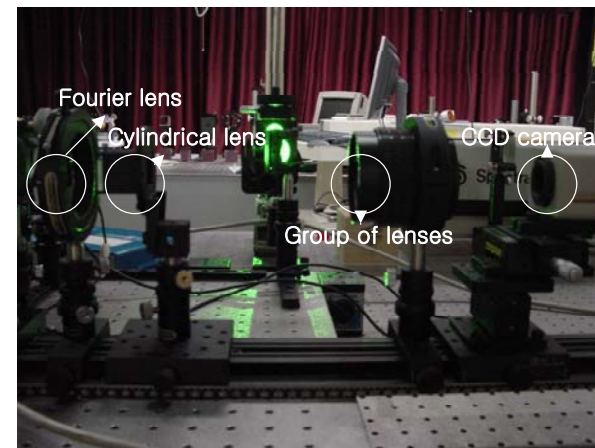 Relay optics: data page scaling for detector

  (SLM pixel size: $36\mu m \times 36\mu m$, CCD camera pixel size: $9\mu m \times 9\mu m$)

  => Aberration suppressed
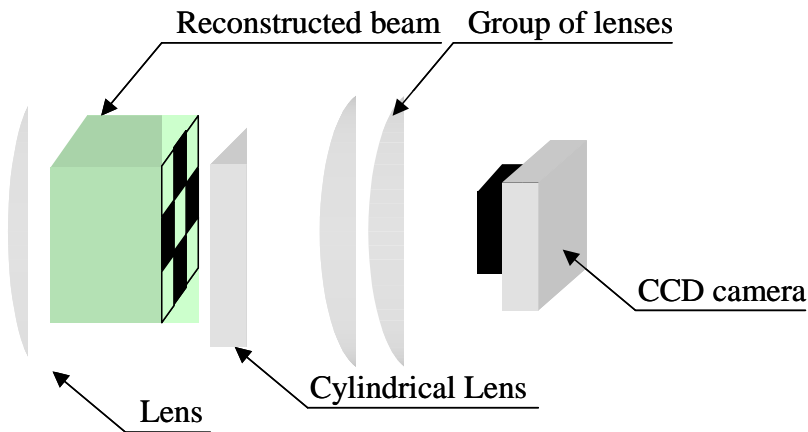
Designed imaging system

Realized imaging system

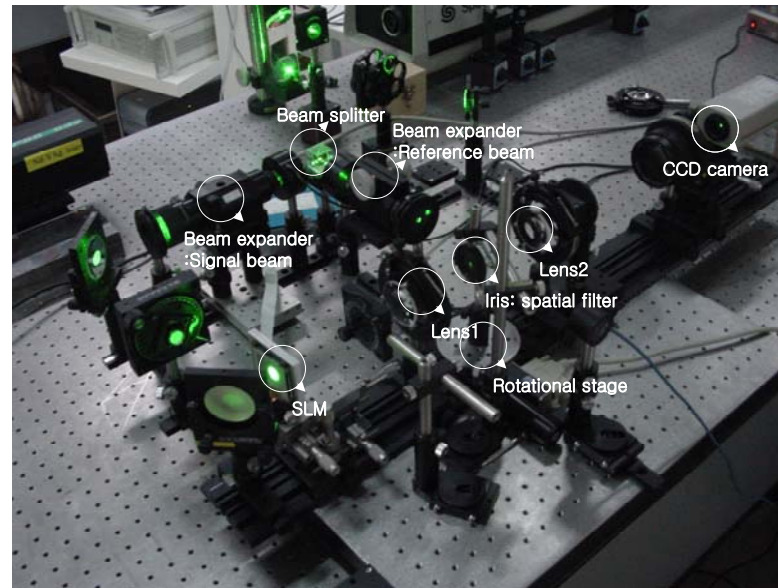**National Creative Research Center for Active Plasmonics Applications Systems**
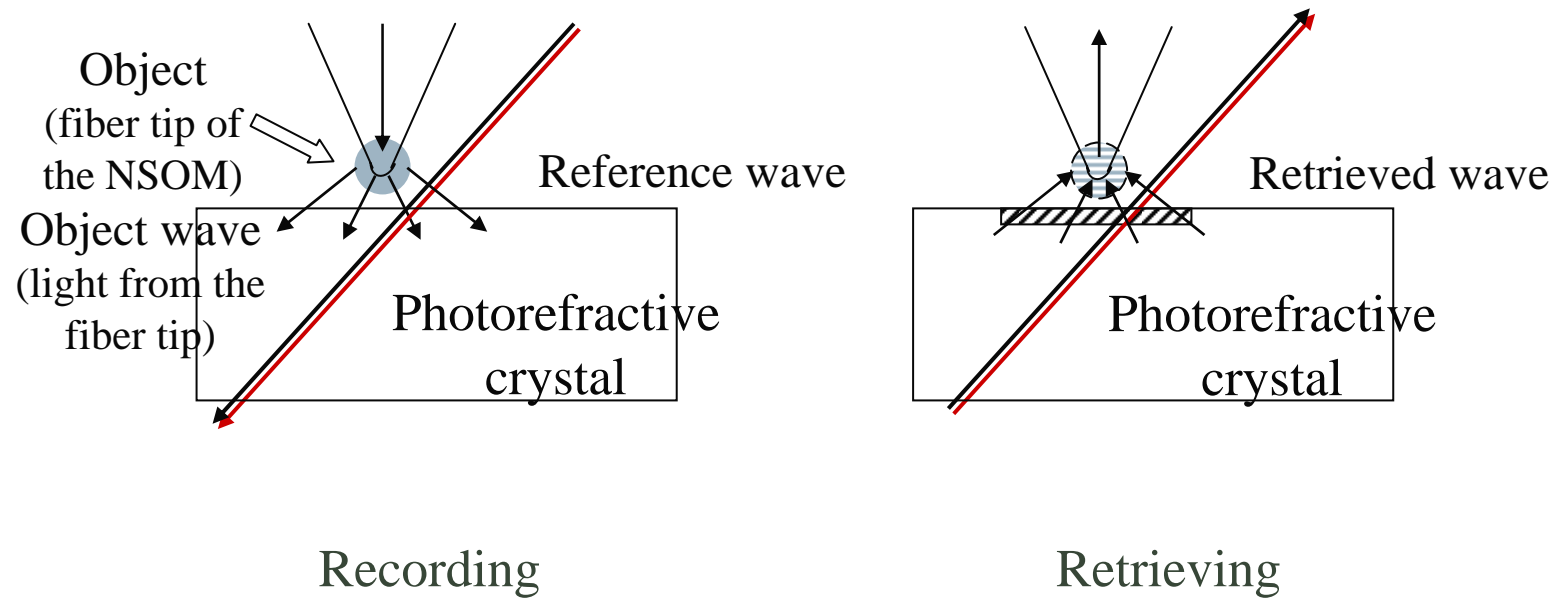
HDS specification

- Angular multiplexing (extension possible with spatial multiplexing)

- Data page : 1/16Mbit

- Storage capacity : > 100 Mbit (1/16Mbit x ~1000 pages with extension)

- Data transfer rate : 1Mbit/s (1/16Mbit x 16 frame/s)

- LabVIEW-based synchronization
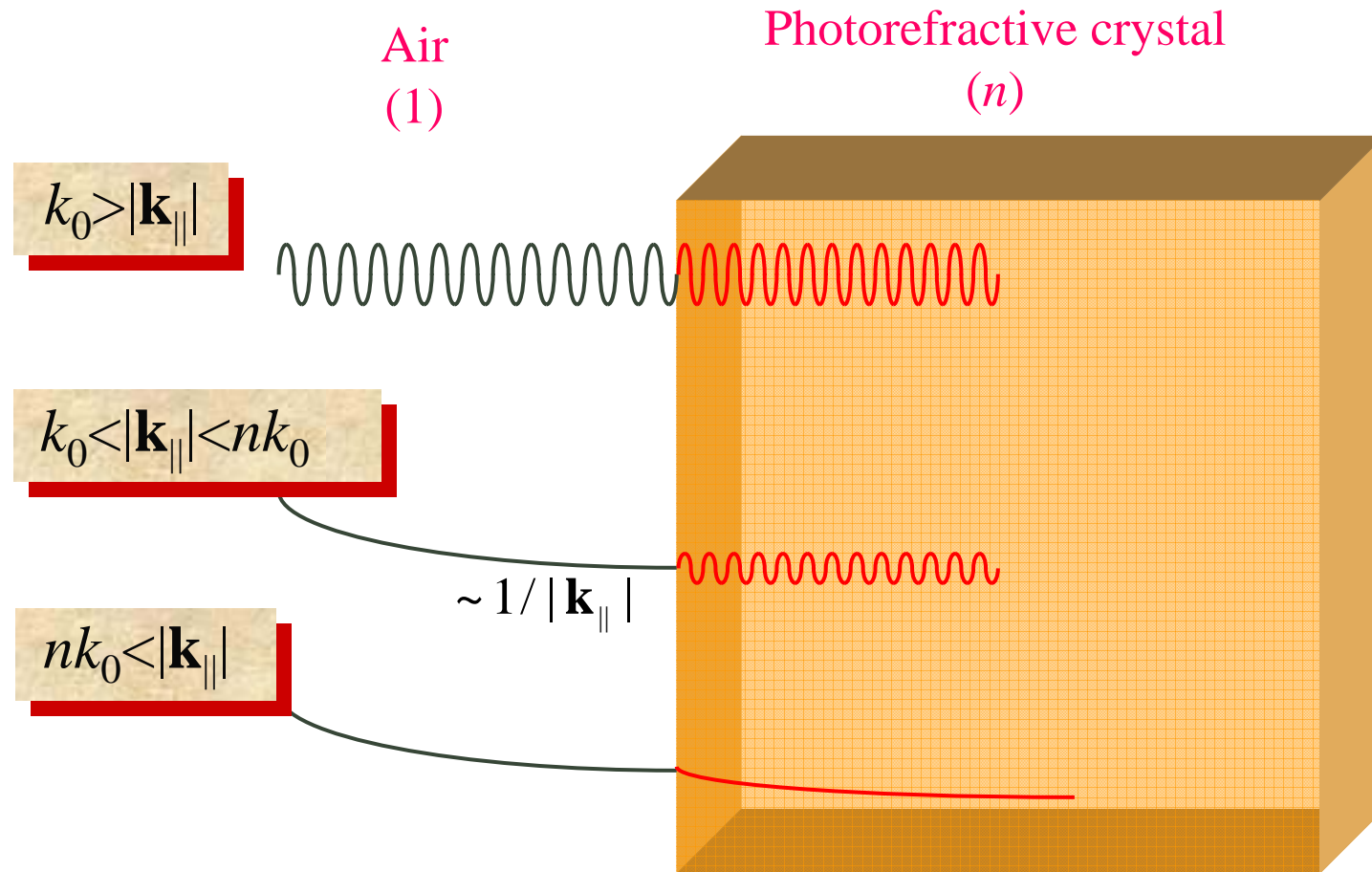
Realized HDS System

Near-field Hologram Storage
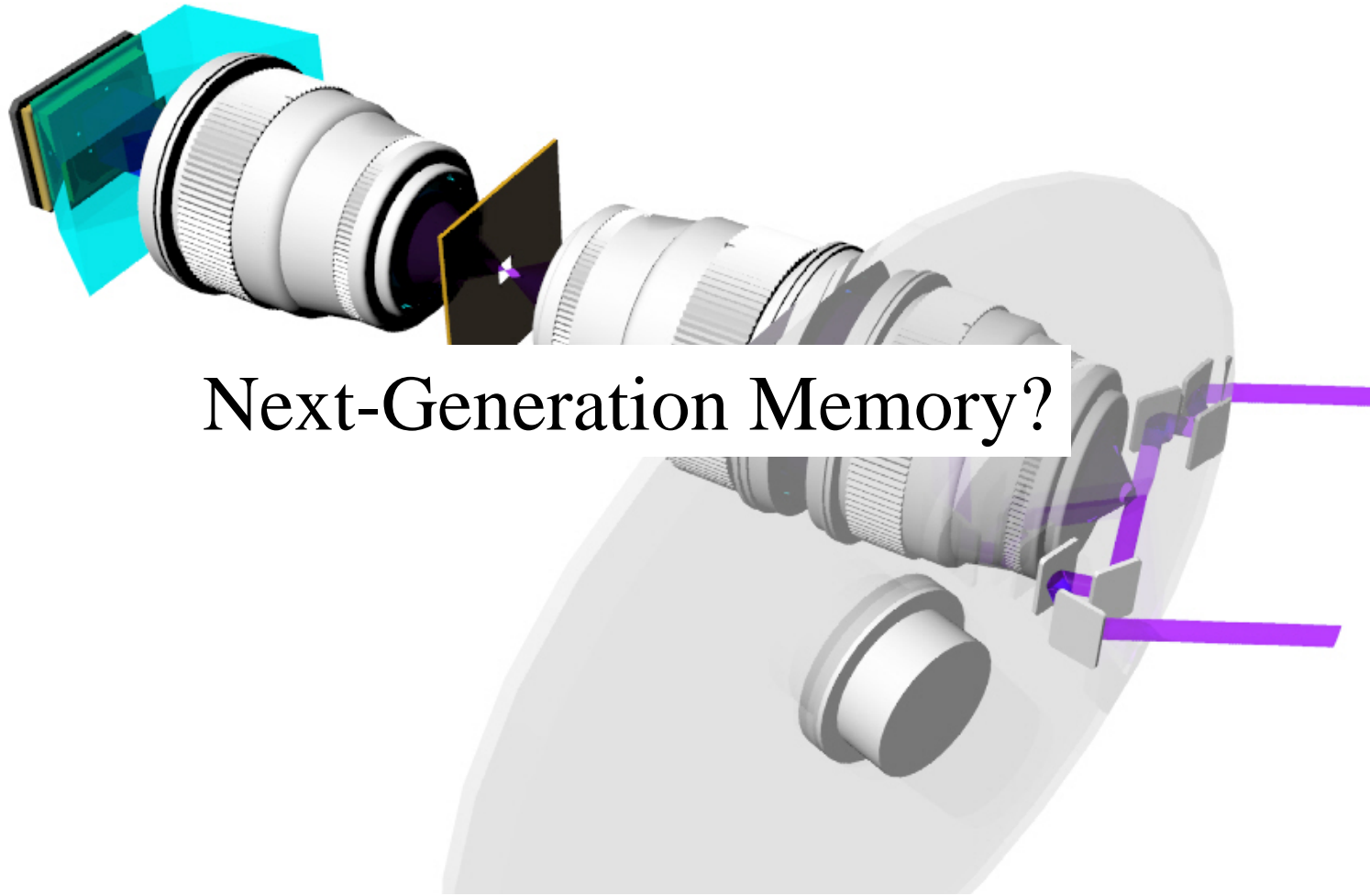
Object
(fiber tip of
the NSOM)

Object wave
(light from the
fiber tip)

Reference wave

Photorefractive
crystal

Recording

Retrieved wave

Photorefractive
crystal

Retrieving

Field Components

Air
(1)

Photorefractive crystal
(n)

$k_0 > |\mathbf{k}_\parallel|$

$k_0 < |\mathbf{k}_\parallel| < nk_0$

$\sim 1 / |\mathbf{k}_\parallel|$

$nk_0 < |\mathbf{k}_\parallel|$

Next-Generation Memory?

Milipede: A Complete Scanning-probe Storage System (IBM)

Possible Alternatives to Magnetic Data Storage
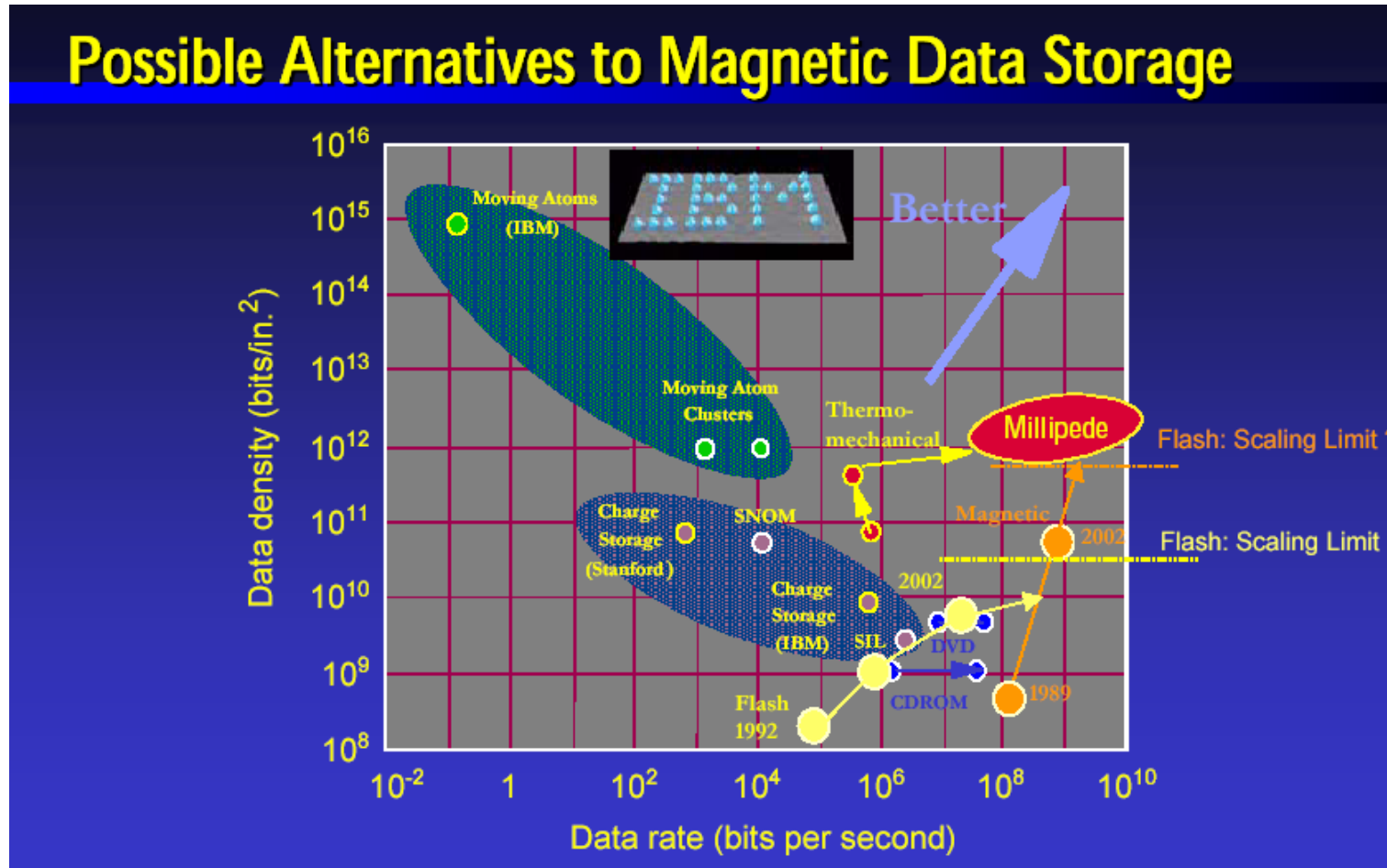
National Creative Research Center for Active Plasmonics Applications Systems

Milipede: A Complete Scanning-probe Storage System (IBM)

- Cantilevers with integrated write/read/erase functionality
  - fast tip heating for writing/erasing
  - highly sensitive sensing for reading

- Dense and large 2-dimensional cantilever array chips
  - VLSI of Micro/Nanomechanics

- CMOS write/read channel electronics
- Cantilever array – CMOS chip interconnect technology
- Polymer medium definition/synthesis
- Micromechanical X/Y scanner
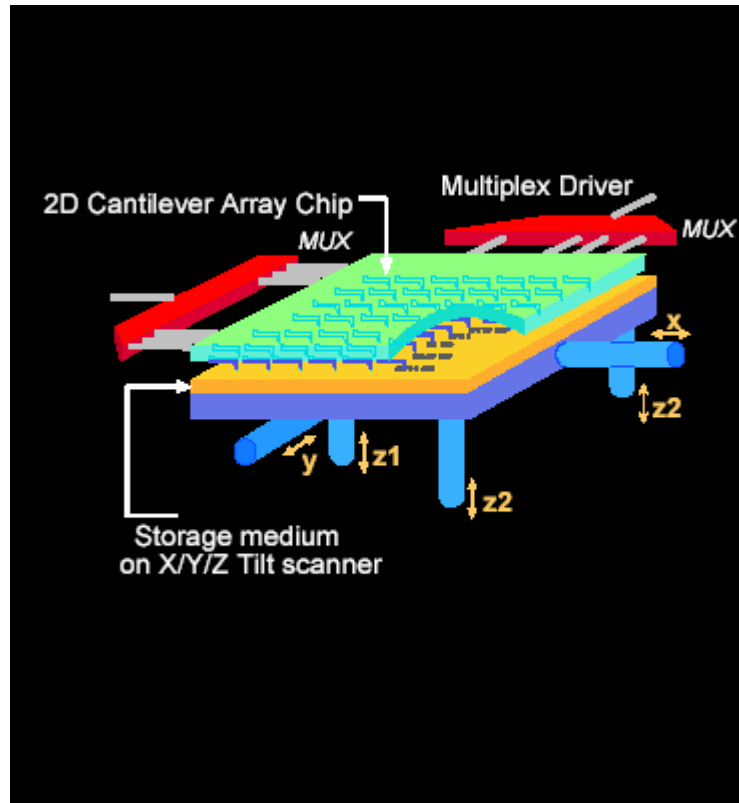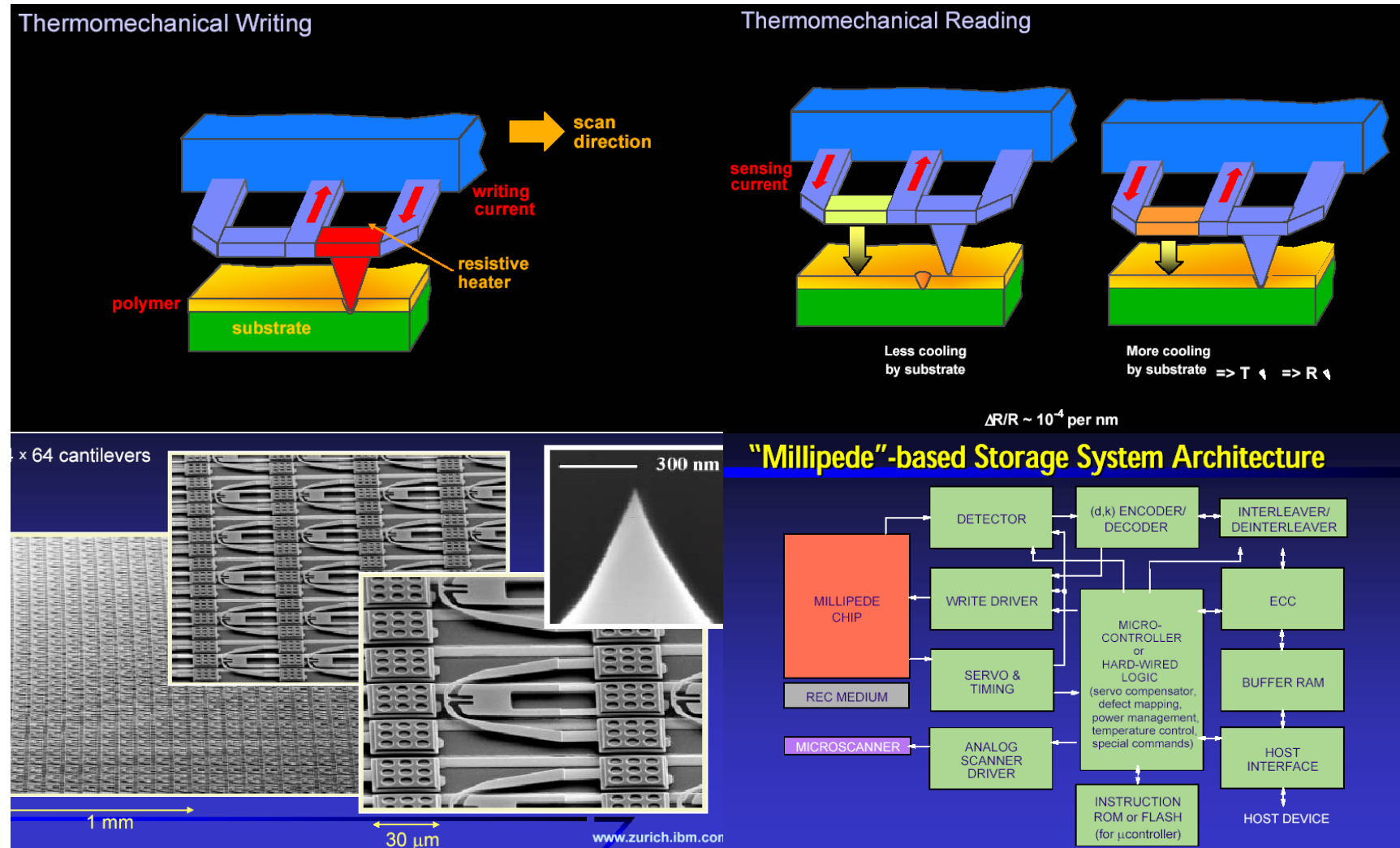- Servo control and navigation of scanner
- Error-correction coding

Milipede: A Complete Scanning-probe Storage System (IBM)

National Creative Research Center for Active Plasmonics Applications Systems