Ultra-high transfer rate high capacity holographic disk digital data storage system.

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Outline

- **Basic holographic disk data storage architecture;**

- **Optical system and holography;**
- **1 Gbit/sec HDSS electronics and synchronization;**
- **Polaroid CROP ULSH-500 recording media;**

- **1 Gbit/sec end-to-end demonstration;**
- **10 Gbit/sec ultra-high speed demonstration;**

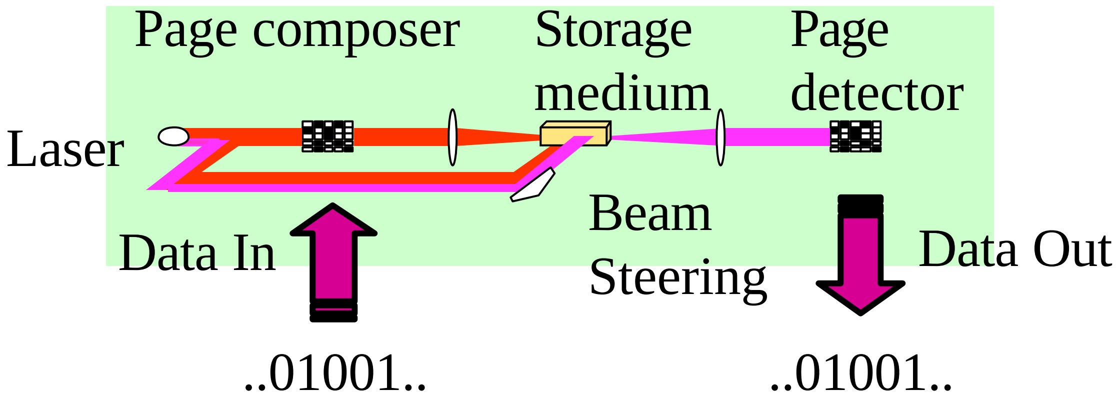
- **Summary.**

Acknowledgments

- **Stanford:**
  - Eric Bjornson;
  - Lambertus Hesselink (PI);
  - Xiachun Li;
  - Sergei Orlov
  - Loukas Paraschis;
  - William Phillips;
  - Yuzuru Takashima.
- **Siros Technologies:**
  - Dave Davies;
  - Harold Harrigan;
  - Frank Kozar;
  - Darren Kwan;
  - Robert Okas;
  - Ray Snyder.
- **Polaroid/Aprilis:**
  - Richard Ingwall;
  - David Waldman.
- **Coastal Optical Systems/ORA:**
  - James Kumler;
  - Don Koch.
- **DARPA:**
  - L. N. Durvasula

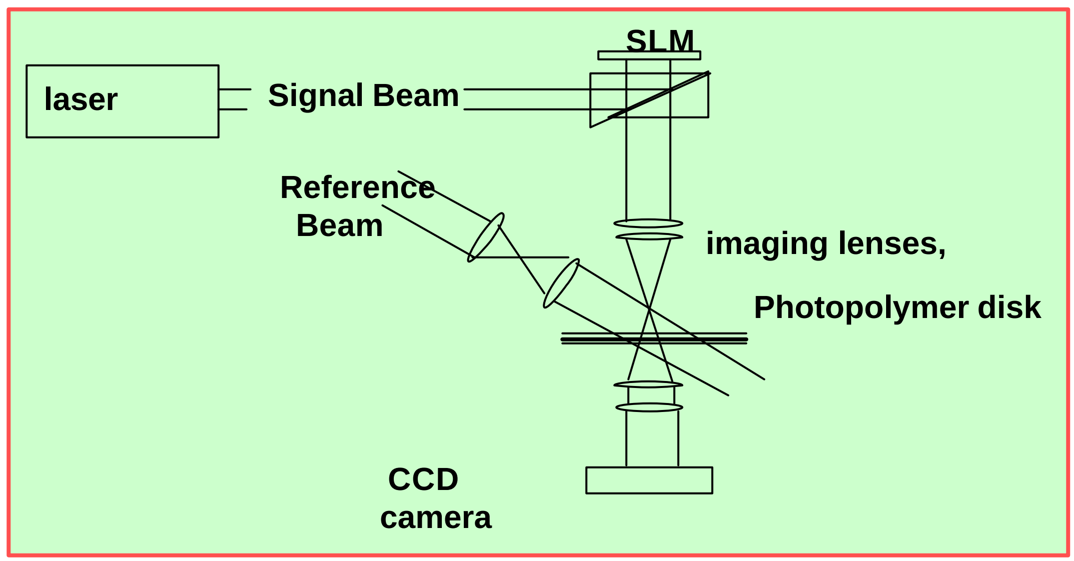
- **Part of this work was been performed under support from DARPA/NSIC Holographic Data Storage Systems (HDSS) and Photo Refractive Information Storage Materials (PRISM) Consortia.**

Architectures for Thin and Thick Media

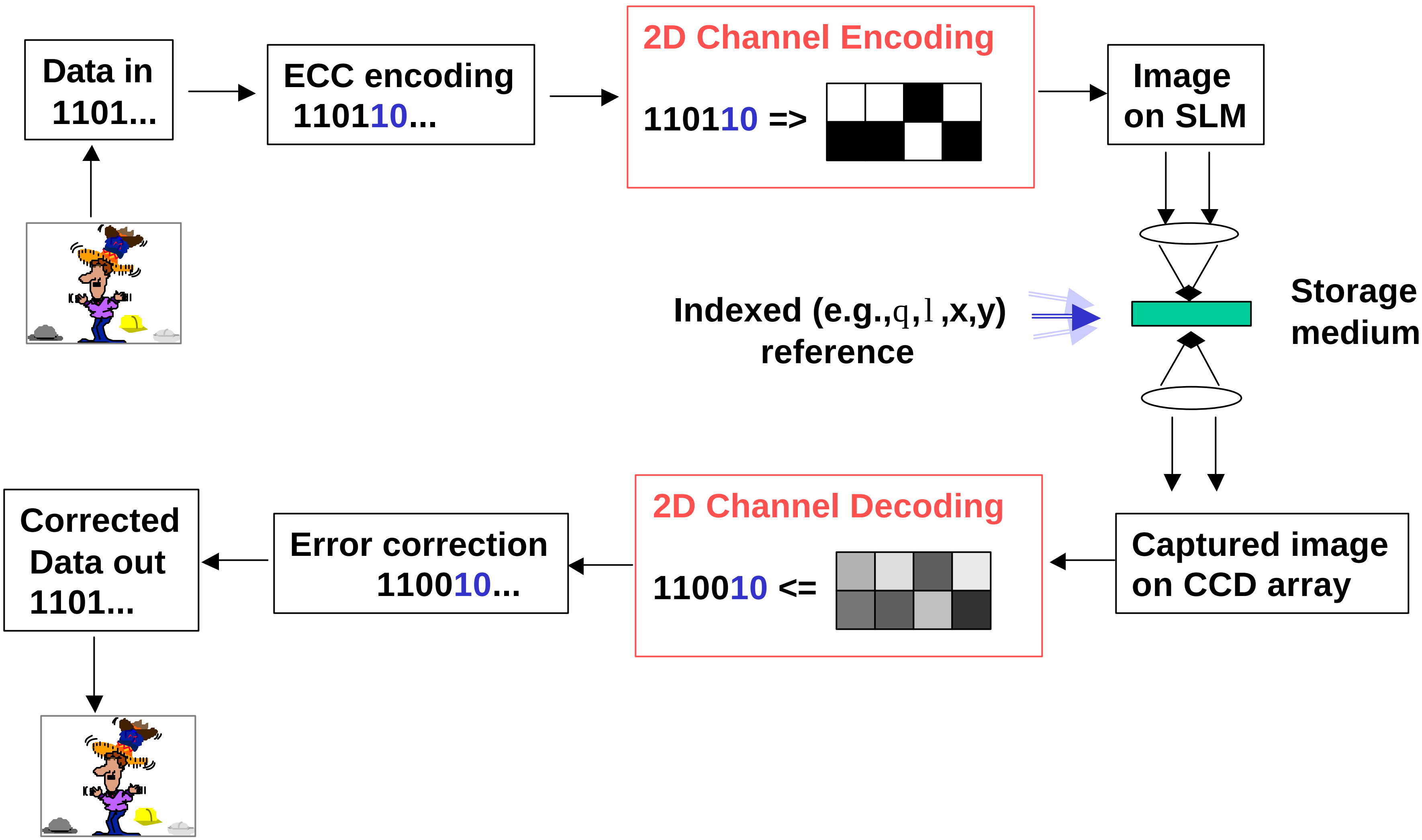


Thick volume medium,
angular/phase multiplexing,
high bit density
(>100 bits/μm^2).

Rotating disk format,
thin volume medium,
massive spatial multiplexing,
(shift or correlation),
high data rate, high capacity.



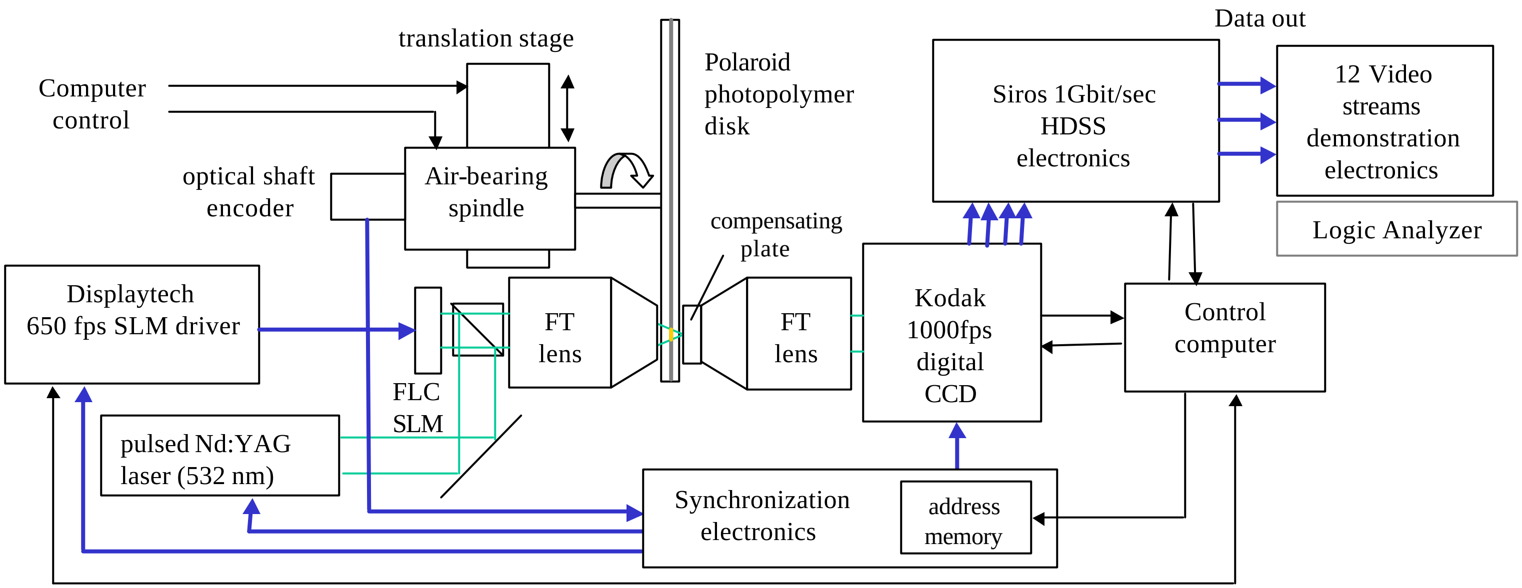
Digital holographic storage: binary patterns vs. analog images



Design considerations for high data rate high capacity system

- **Holographic disk architecture:**
  - high data rate can be realized with rotating disk + pulsed laser source,
  - high capacity achieved by massive spatial multiplexing (large media area),
- **High NA low distortion imaging optics:**
  - high bit density per hologram for high capacity at high data rate;
  - ~0.5 bit/μm^2 density per hologram;
  - shift/correlation multiplexing for multiple superimposed holograms.
- **Hardware implemented channel, ECC decoding, and deconvolution electronics (for 1 Gbit/s data rate)**
  - rate efficient channel code, implementable in FPGA electronics => **6:8 encoding;**
  - 3 × 3 deconvolution using COTS electronic components.
- **Material - Polaroid CROP photopolymer:**
  - large M/# (>10.0 for plw), low shrinkage (<0.1%),
  - high sensitivity (S > 1000 cm/J),
  - thickness 200 to 500 μm.

Overall architecture of Stanford/HDSS holographic disk system



Stanford/HDSS holographic disk system

Holographic disk system components

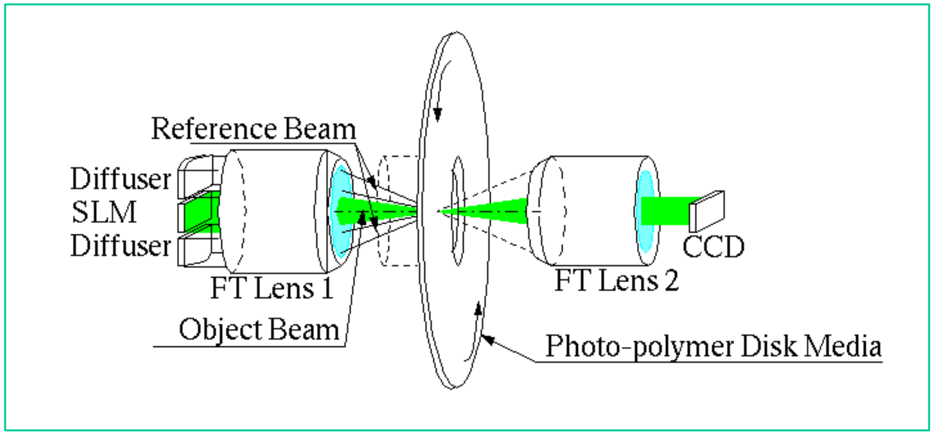
- **<u>Low shrinkage material:</u>**
  - Polaroid ULSH-500 photopolymer disk
    - S > 1000 cm/J
    - M/# > 2.4;
    - thickness 500 μm/200μm;
    - thermal precure;
    - low shrinkage (ε < 0.1%).
- **<u>High NA imaging optics:</u>**
  - F=17.1mm double Fourier transform;
  - Total field of view 38 mm (dia) (including diffuser);
  - Imaging area: 13.1×13.1 mm^2
  - low distortions (<0.25 pixel);
  - NA_{pix} = 0.035;
  - ζ = 1.7
  - Fourier stop: 1.1 × 1.1 mm^2;
  - Hologram spot area: ~2 mm^2,.
- **<u>Electronics/laser/transport system</u>:**
  - Seagull air-bearing spindle 300 RPM, optical shaft encoder, 40 nm edge position accuracy;
  - Newport PM600, 25 nm repeatability;
  - laser: 500μJ/pulse, 25 nsec Nd:YAG;
    - < 5 nsec rms. timing jitter;
  - 1000 fps CCD and
  - 1 Gbit/s decoding electronics,
  - Synchronization electronics,
  - IBM FLC SLM.
- **<u>Shift/correlation Multiplexing</u>:**
  - 4^o FWHM diffuser to generate speckle reference;
  - Correlation distance ~1.2 μm;
  - $\delta x = 5\ \mu$m;
  - $NA_{speckle}$ = 0.4
  - Density = 0.5 bits/μm^2/hologram.

Optical system

and

holographic correlation multiplexing

Single-head optical design: High NA Double Fourier transform imaging with integrated reference optics



High NA imaging optics:

F=17.1mm double Fourier transform lens pair;

12 element design, high-index glass (ORA, Stanford);

Total field of view 38 mm (NA = 0.75)
(including reference diffuser);

Imaging area: 13.1×13.1 mm^2 (**NA = 0.39**)

Low distortions (<0.25 pixel over entire SLM field);

Fourier stop: 1.1×1.1 mm^2 ($\zeta = 1.7$);

Hologram spot area: ~2 mm^2,

Storage density: 0.5 bits/μm^2 per hologram.

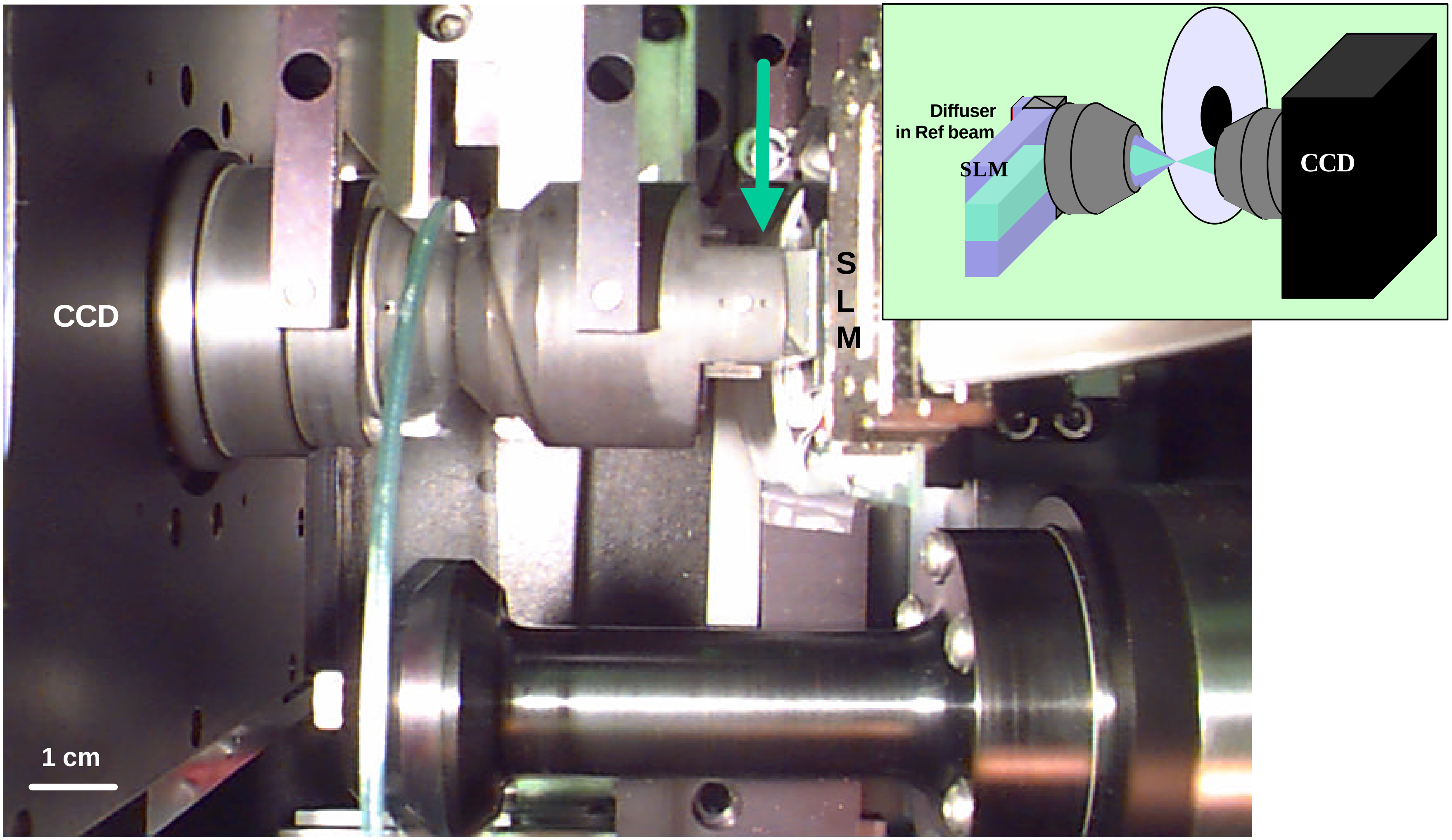
Storage density:

$$D = \left(\frac{d}{z\,l\,F}\right)^2 \times N,$$

$$D = \left(\frac{2\,NA}{z\,l}\right)^2 \times N,$$

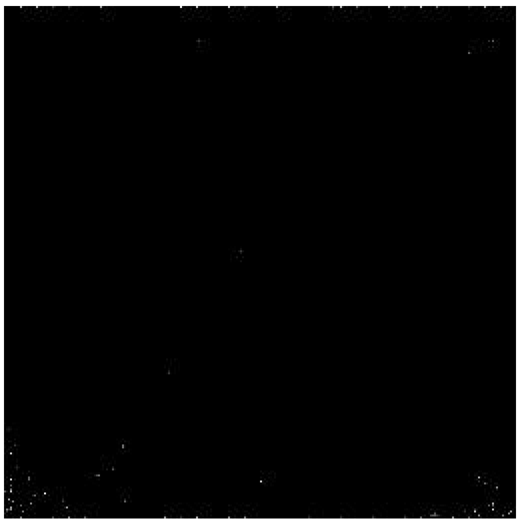
N - number of superimposed holograms;
Multiplexing using speckle correlation mux.

Double Fourier transform lens pair (top view)
manufactured by Coastal Optical Systems



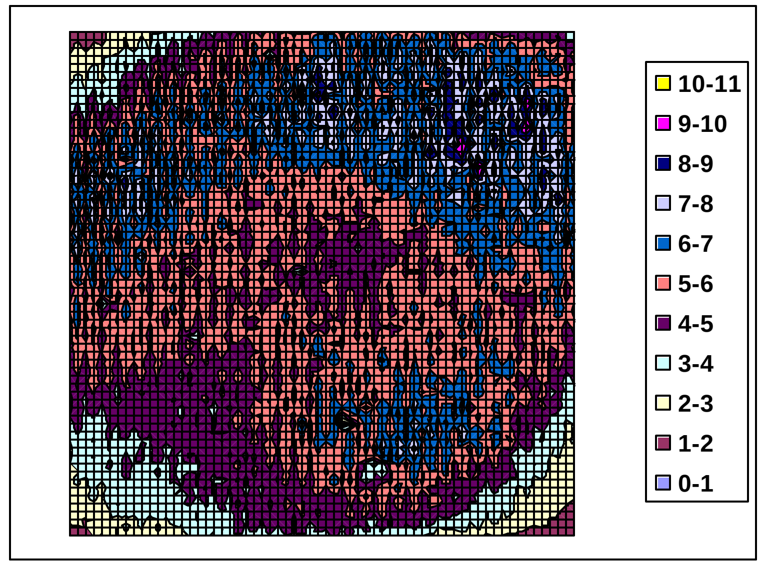
Imaging, low distortion Double Fourier transform lens

Error map (0.1% area - corners)



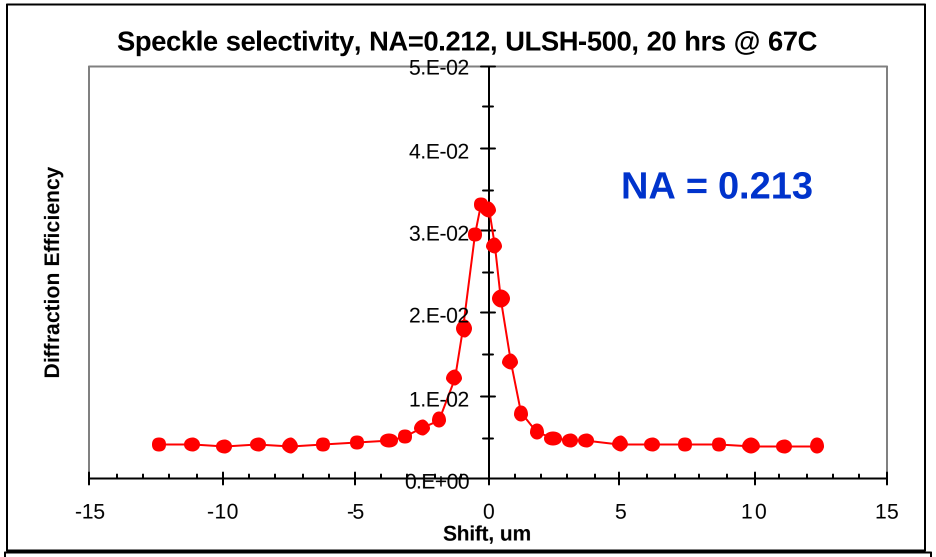
SNR map

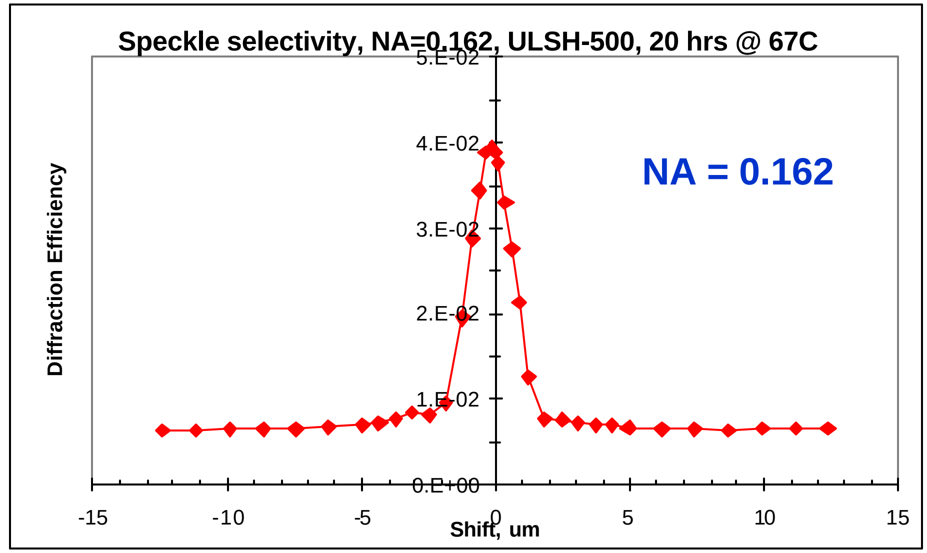
$$SNR = \frac{\langle S \rangle - \langle N \rangle}{\sqrt{s_S^2 + s_N^2}} \equiv \frac{\langle "1" \rangle - \langle "0" \rangle}{\sqrt{s_{"1"}^2 + s_{"0"}^2}}$$

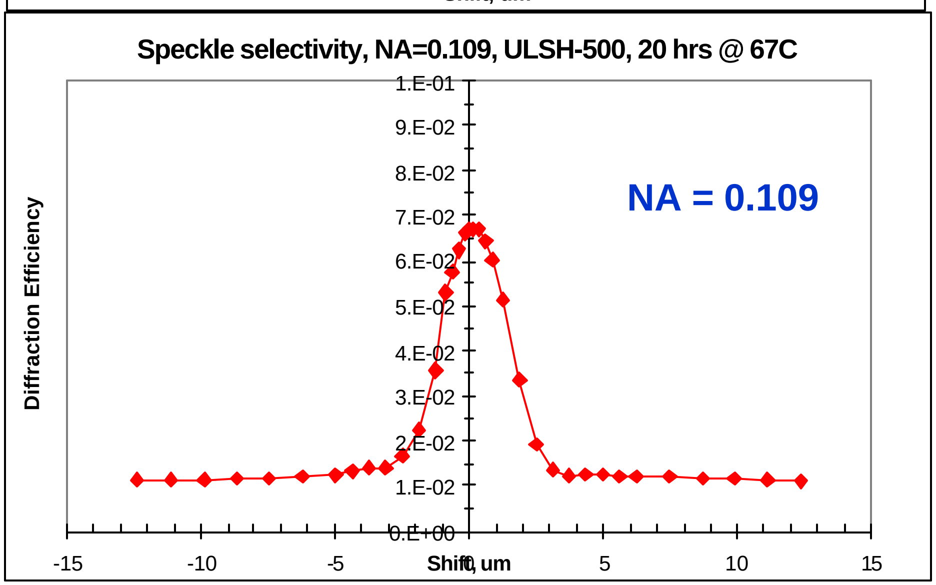


- **Imaging distortion are < 0.25 pixels over entire SLM format (from Moiré pattern meas.);**
- **Both magnification and decenter compensators are implemented on second objective;**
- **Further image correction using hardware implemented 3×3 pixel deconvolution;**
- **Data interleaving for uniform BER (before ECC).**

Correlation shift speckle multiplexing
(Gaussian speckle field as a reference beam)







Decorrelation (A.Darskii and V.V.Markov, Proc. SPIE **1600**, 318 (1992)):

$$h(d) = h_0 \,|\, 2 J_1 (k\,NA\,d)/(k\,NA\,d)\,|^2$$

$$d_x\,(\mathrm{FWHM}) \sim 1.2\, l / NA\,,$$

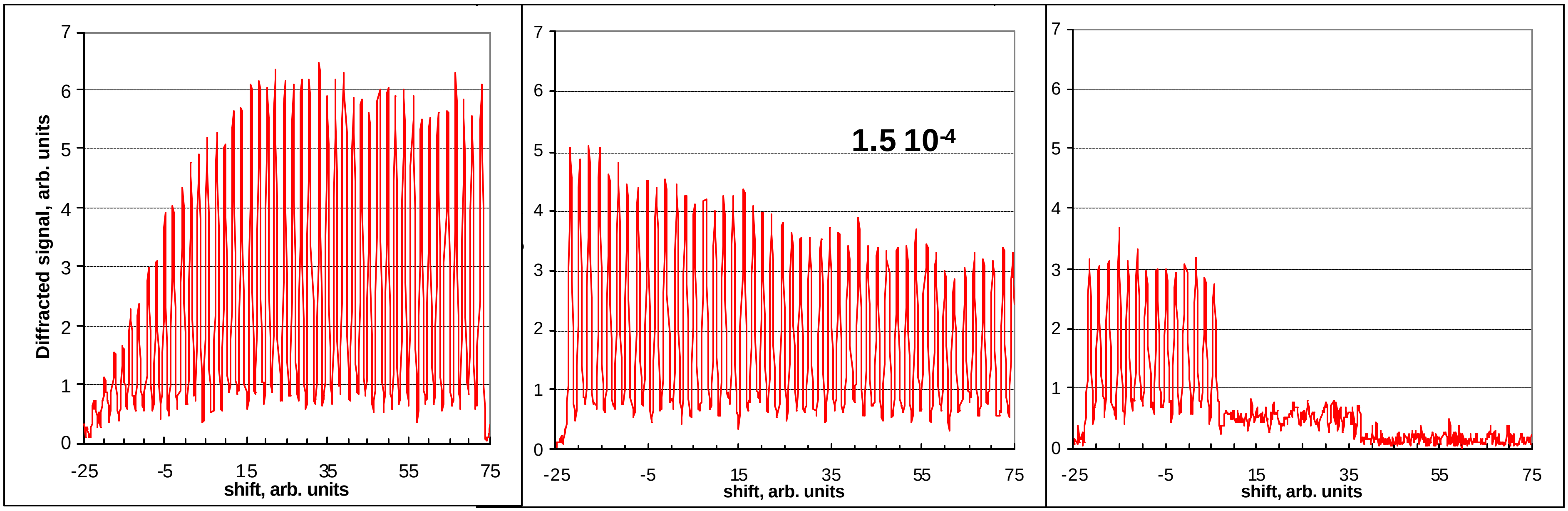
$$d_y\,(\mathrm{FWHM}) \sim 1.2\, l / NA\,.$$

- d_x, d_y **are determined by speckle autocorrelation;**
- **selectivity is independent of shift direction;**
- **selectivity is independent of media thickness;**
- crosstalk buildup depends on shift direction and thickness.

Superimposed holograms recorded in Polaroid 200 μm photopolymer with speckle reference

100 Holograms (exposure = 0.5mJ/cm^2 each)

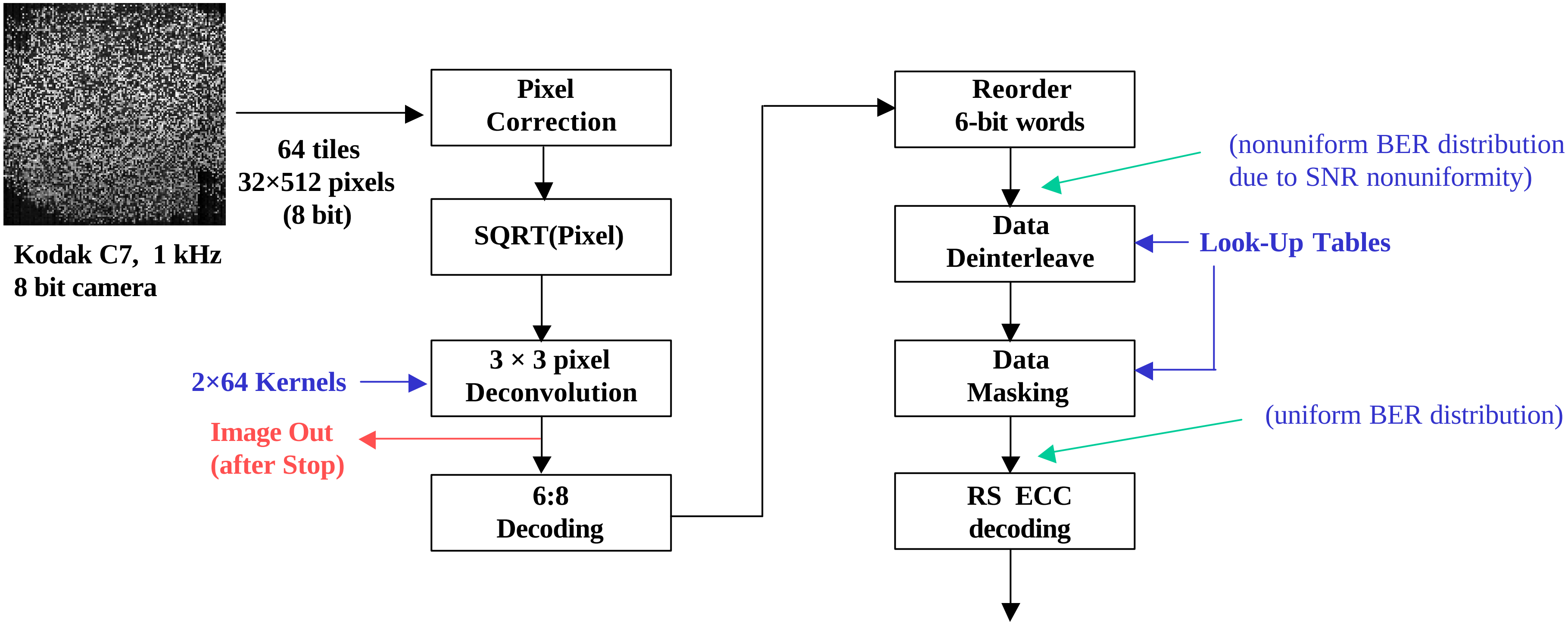
Holograms are recorded with ~ 5 μm shift of the media between each exposure.



M/# = $\Sigma\ \eta^{1/2}$ = <u>0.98;</u> **NA$_{speckle}$ = 0.21;** **NA$_{signal}$ = 0.015**

HDSS Electronics

1 Gbit/sec Siros/Stanford/HDSS hardware electronics operation



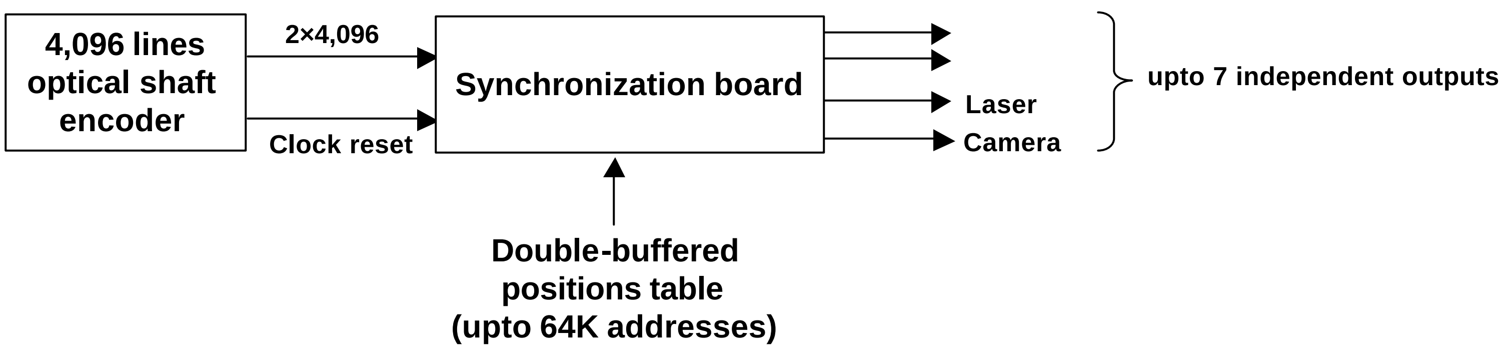
output
12 Byte streams 10MHz
960 Mbit/sec

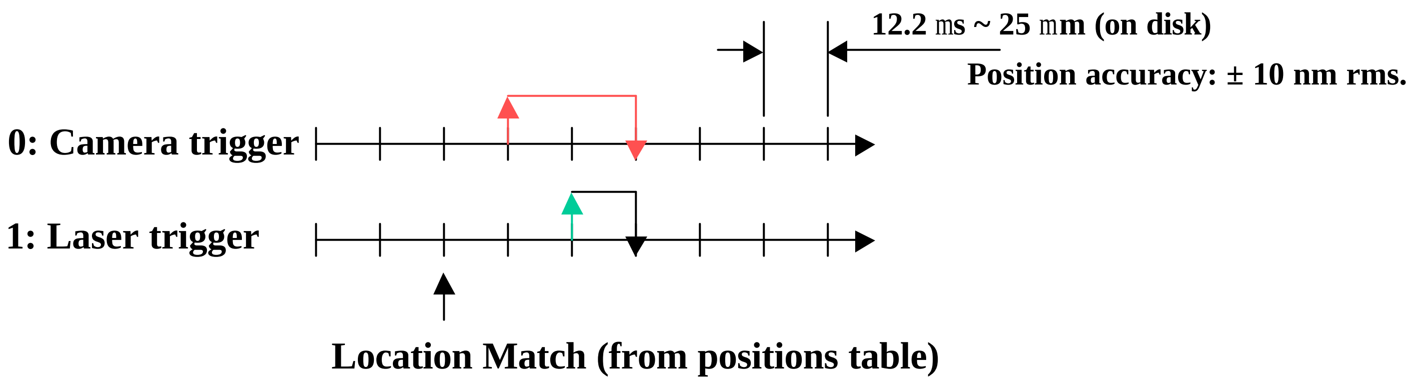
- **1 Gbit/s HDSS electronics:**
  - 16 6:8 decoder boards (4 chan./board);
  - 1 Multiplexer board;
  - 1 ECC board (3 RS chips);
  - 1 Synchronization board (disk/laser/camera/SLM);
  - PCI-VME Bridge;
  - Electronics is implemented using reprogrammable FPGA and CPLD electronic components.

Rotating disk/laser/camera synchronization

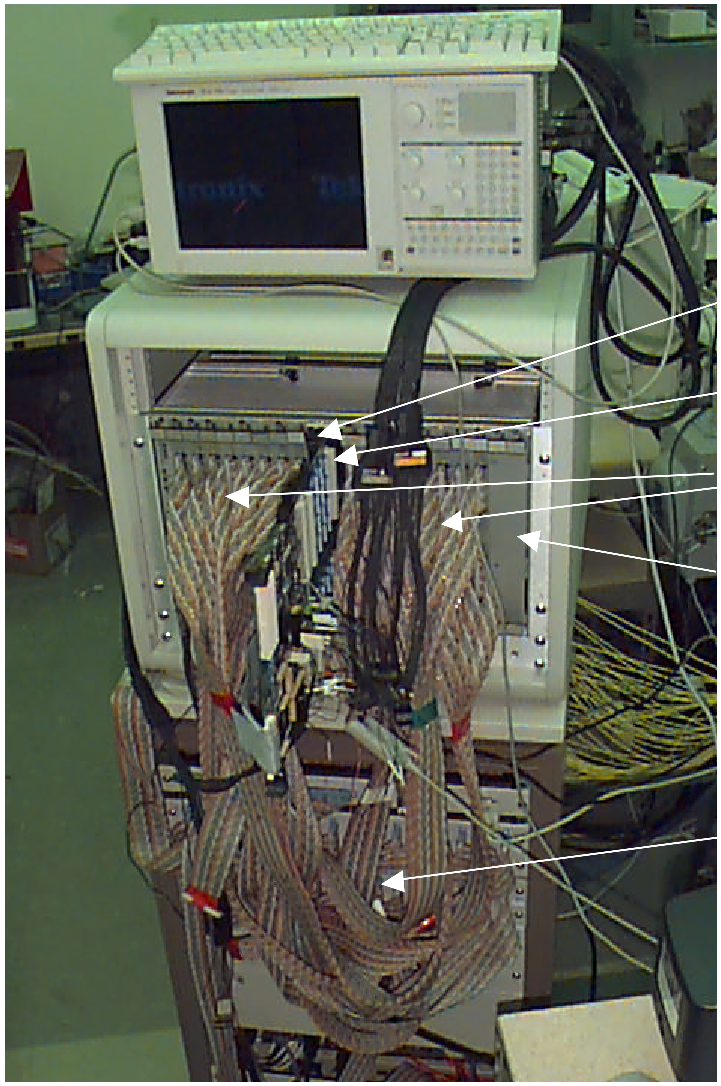
- **Disk position is derived from optical shaft encoder (4,096 2× quadratures);**
- **Encoder: < 10 nsec rms edge jitter (i.e., <20 nm position error for 16,384 positions on the disk);**
- **Laser: 500mJ/pulse, 20 nsec Nd:YAG;**

  < 5 nsec rms. timing jitter;





Siros/Stanford/HDSS 1 Gbit/sec electronics



ECC Board

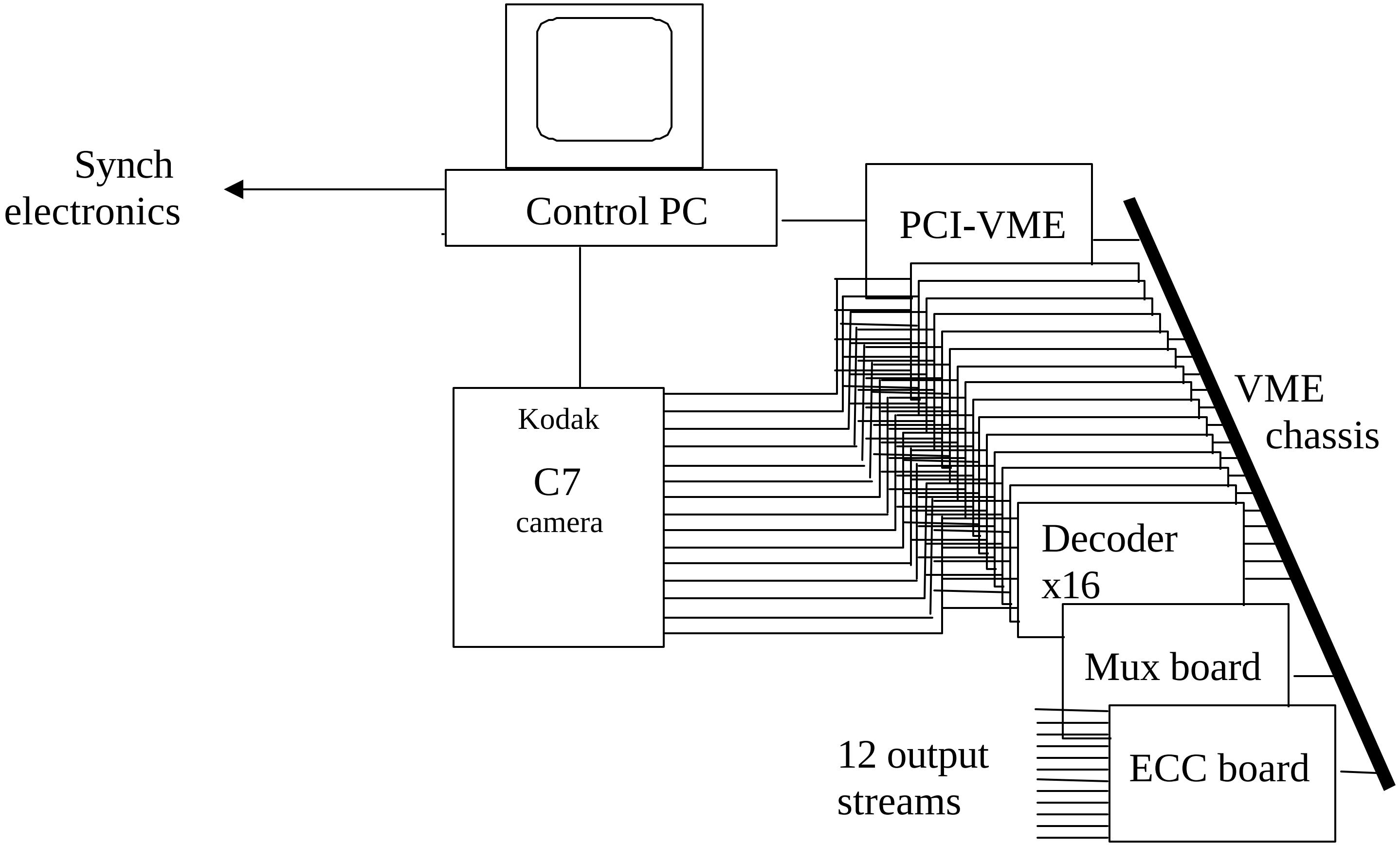
Multiplexer board

Decoder boards (16)

Synchronization board

Kodak C7 camera electronics

Siros/Stanford HDSS electronics

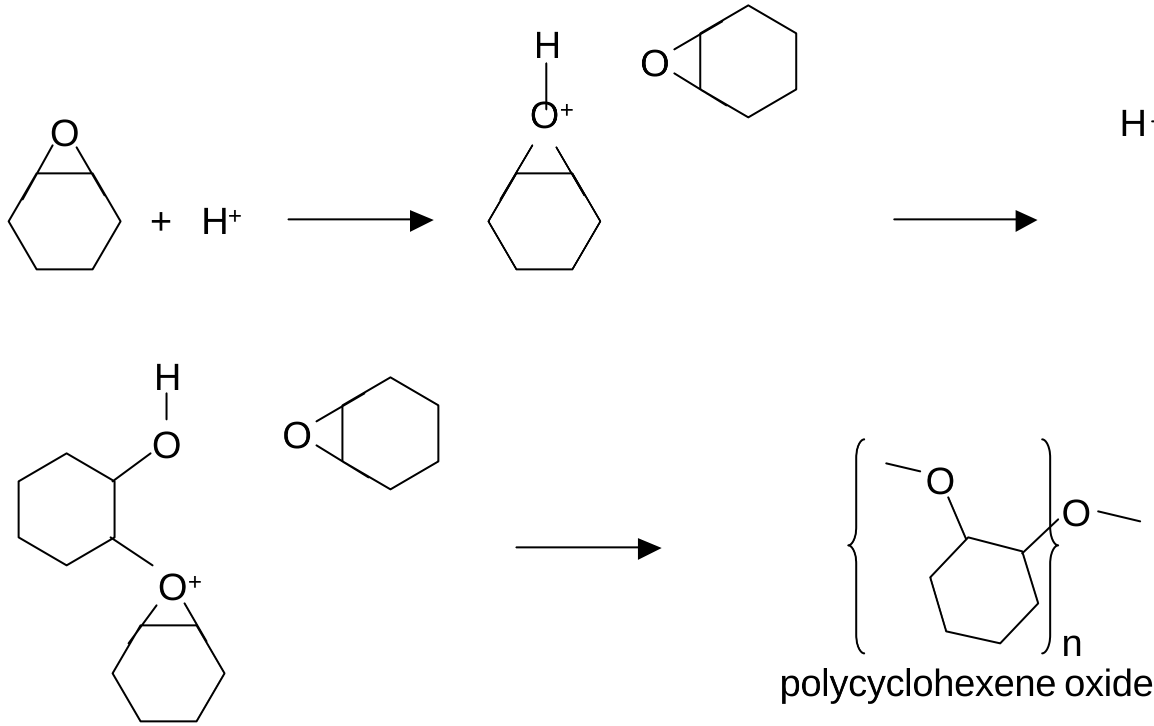


Holographic recording material: Polaroid CROP photopolymer

Recording material: Polaroid CROP photopolymer

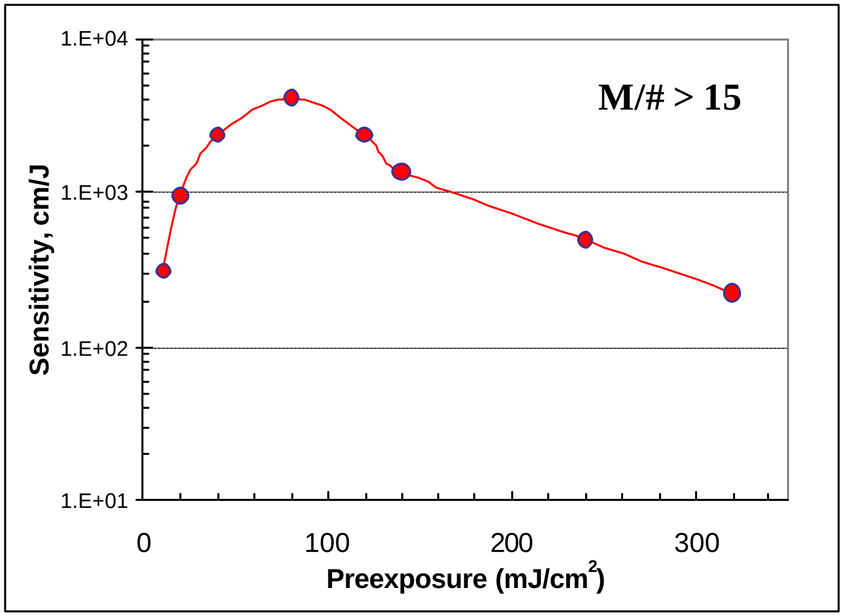
- **Requirements:**
  - large M/# (>10.0 for plw), low shrinkage (<0.1%),
  - high sensitivity (S > 1000 cm/J),
  - thickness 200 to 500 μm.
- **Material: Polaroid Cationic Ring-Opening Polymerization photopolymer;**
- **Composition:**
  - epoxy siloxane-based di- and multi-functional monomers;
  - photoacid generator;
  - photosensitizer dye;
  - binder (siloxane-based).
- **Recording characteristics:**
  - ultra-low shrinkage (after precure) < 0.1%;
  - sensitivity 500 to 3000 cm/J;
  - dynamic range $(M/\#)_{plw}$ up to 20.0, $(M/\#)_{image}$ ~ 2.0;
  - thickness up to 500 μm;
  - optical homogeneity: $BER_{imaging} < 10^{-14}$ (IBM HOST data);
  - scatter: 1.5×10^{-3} srad^{-1}.

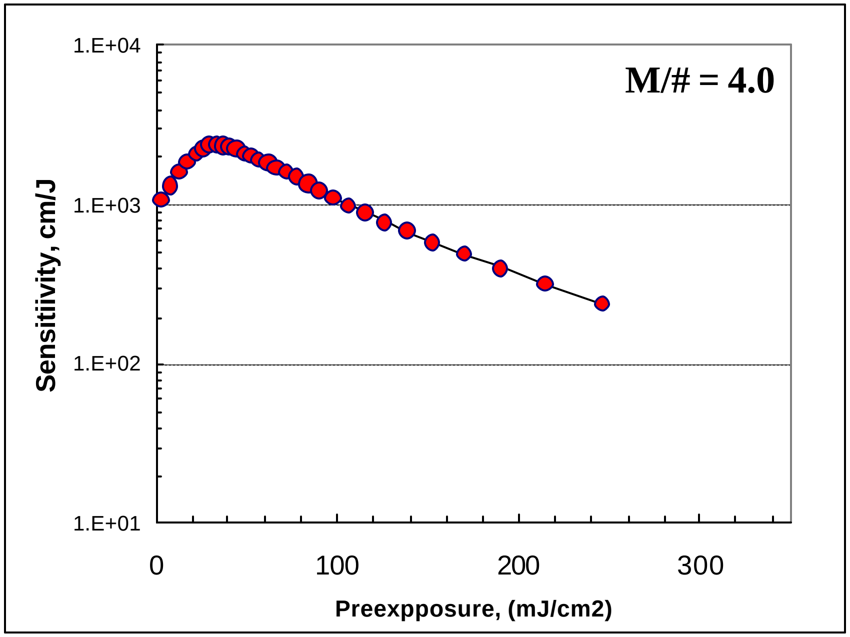
Polymerization and chain propagation in Polaroid CROP



- **Termination:** self-entanglement; reaction with quenching centers, etc.
- Ring opening step reduces shrinkage upon polymerization (ε < 0.1%, at M/# ~ 5.0);
- Index modulation due to diffusion and polymer/binder segregation.

Sensitivity of Polaroid CROP photopolymer

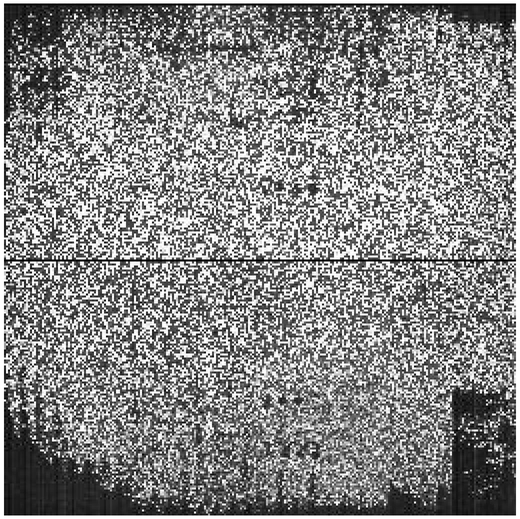




- **optical preexposure/scheduled exposure**
  early stage: viscosity buildup for hologram anchoring.

- **thermal precure/scheduled exposure**
  starting material is already a dry film; higher optical uniformity compared to optical preexposure.

Sample multiplexed hologram recorded in Polaroid CROP using correlation multiplexing



- **500 microns thick recording medium;**
- **Material thermally precured before recording;**
- **Image: 1024×1024 pixels, 6:8 encoding;**
- **Byte error rate: 5 10^{-3} (~ 5% area masked).**

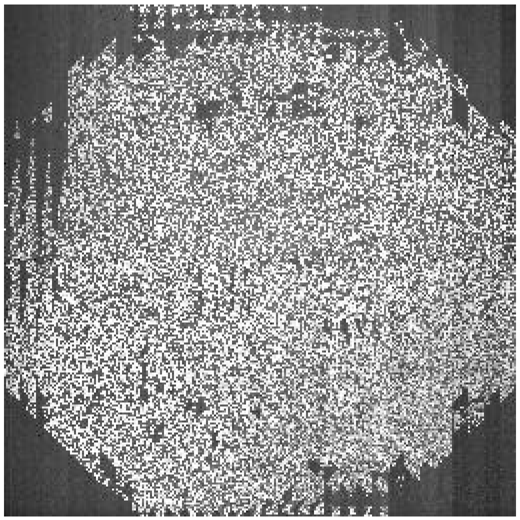
Demonstrations

1Gbit/sec demonstration summary (10/99)

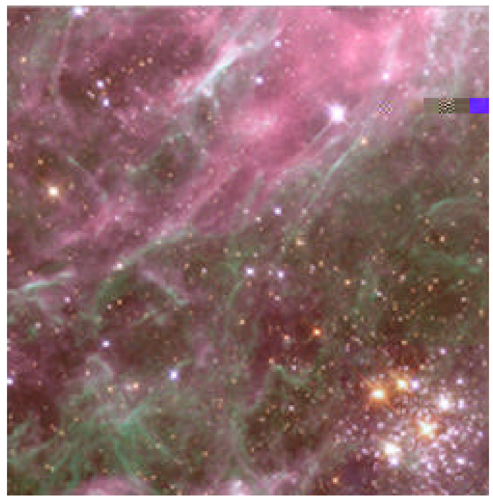
- JPEG image data encoded into SLM images (6:8 code);
- Page capacity = **65.3 Kbytes** (user);
- Holograms were sequentially recorded at 300 RPM disk rotation rate (each hologram was recorded with ~ 12 laser pulses);
- Material: 200 μm Polaroid ULSH-500 6.5” diameter disk;
- Holograms were retrieved at 1 Gbit/sec and channel/ ECC decoded by hardware ;
- Data are captured by Tektronix logic analyzer and converted back to JPEG files.

- **Currently: 12 simultaneous video-streams playback from holographic disk (at 650 fps).**

1 Gbit/sec end-to-end demonstration in Stanford/HDSS holographic disk system



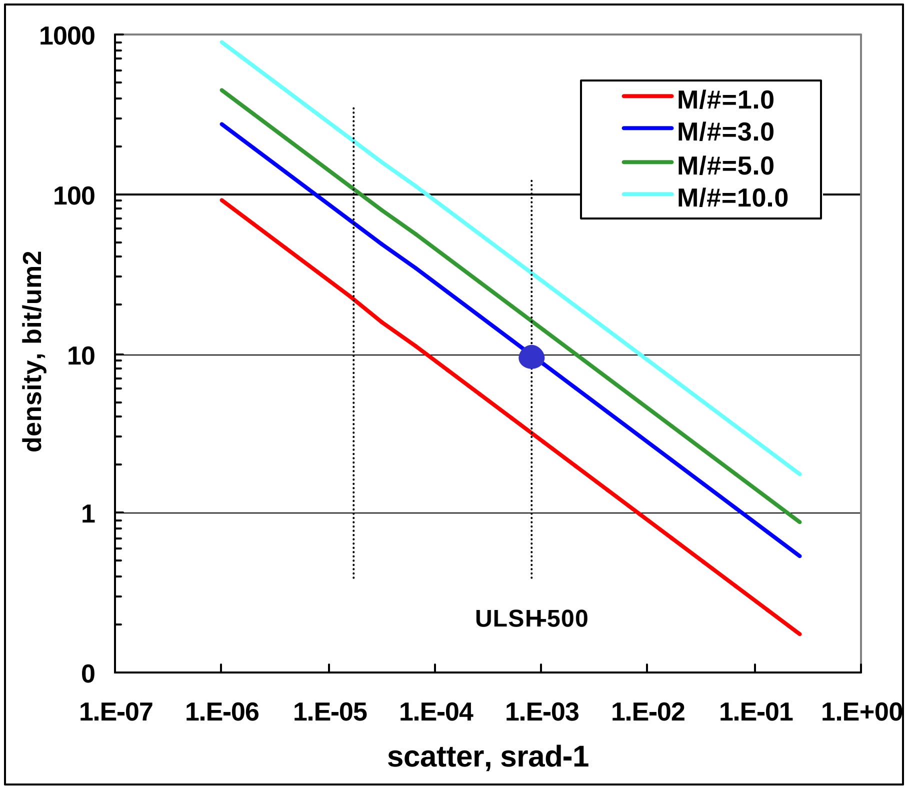
Sample retrieved hologram
Raw Byte error rate: 3×10^{-3}
h **~ 5×10^{-3}**

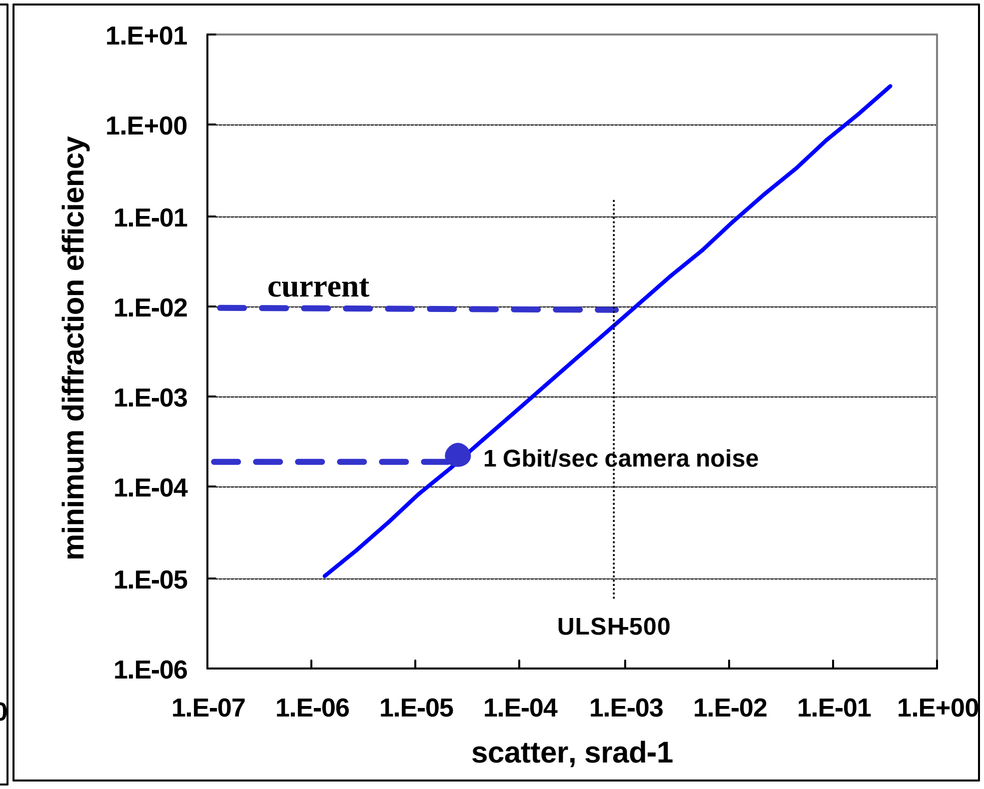


Sample **Retrieved JPEG data**
(data distributed between different holograms).

Original JPEG data

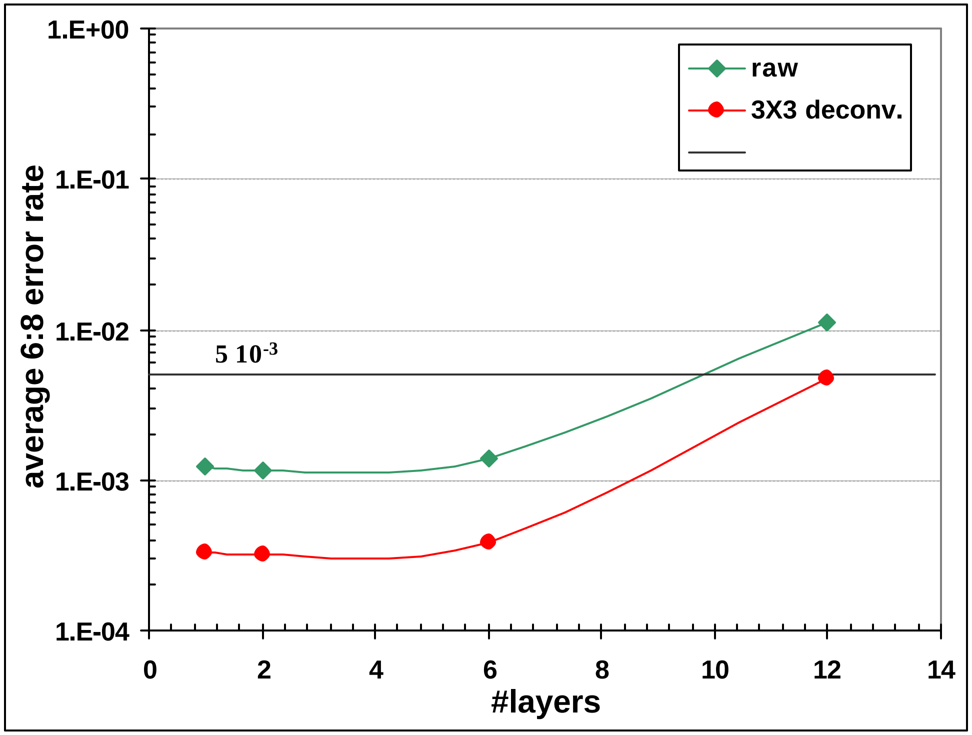
Recording density vs. scatter; HDSS photopolymer disk system





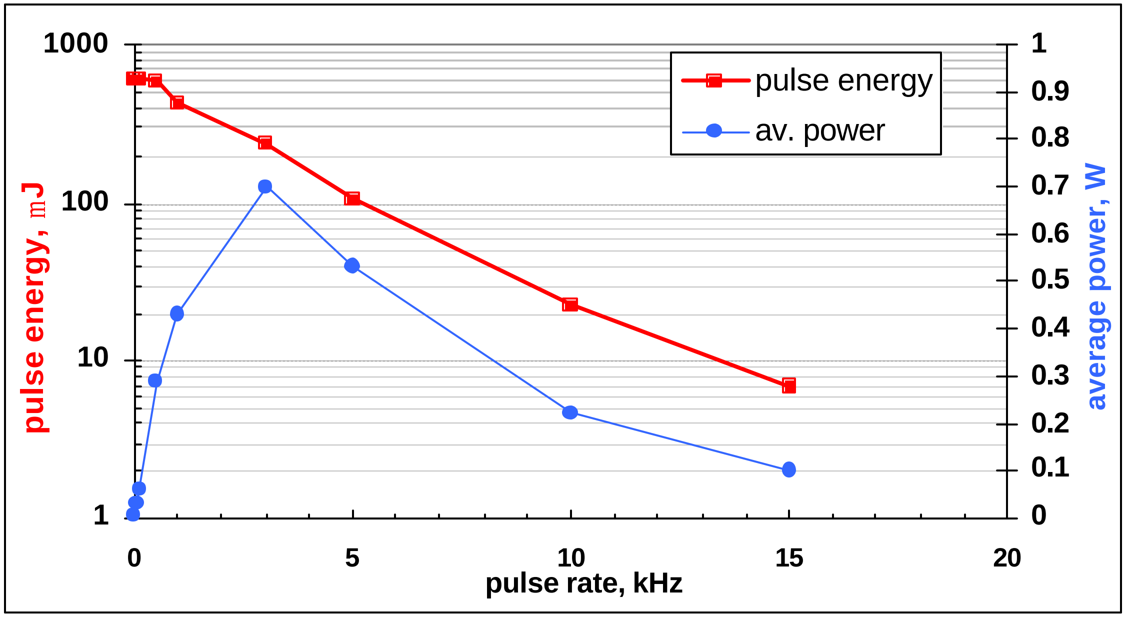
- Material figure-of-merit $\propto$ N of holograms, density $\propto$ **C×(M/#)/ (e Ö $\overline{\text{scatter}}$)**
- **M/# > 3 to 5 is not feasible due to shrinkage distortions.**
- **Recording density is currently ~ 10 bits/μm^2**
- <u>**Signal strength allows faster transfer rates: 10 Gbit/sec and higher.**</u>

Recording density in ULSH-500 photopolymer



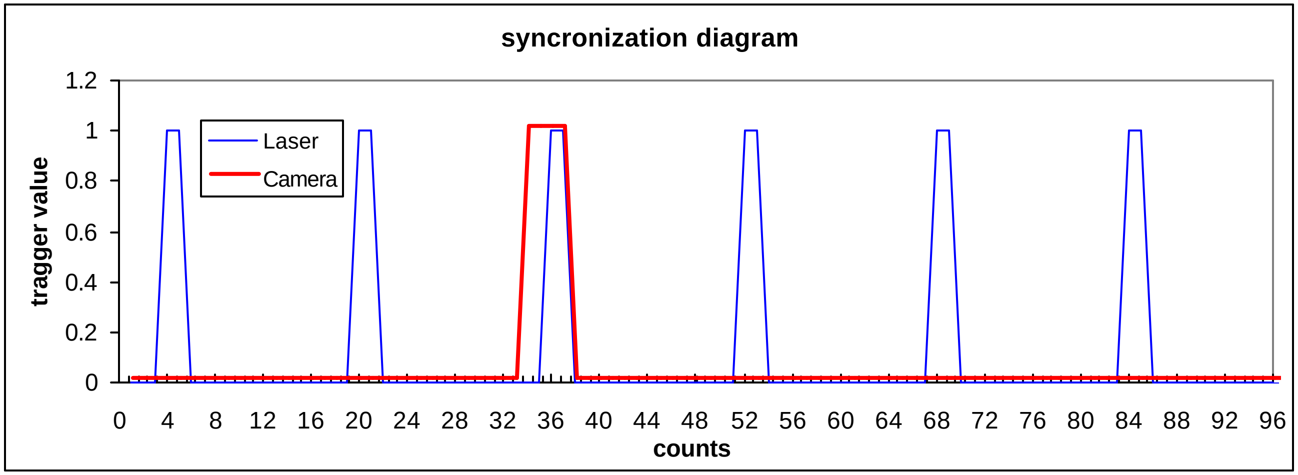
Error rate increases with density due to hologram distortions arising from material shrinkage.

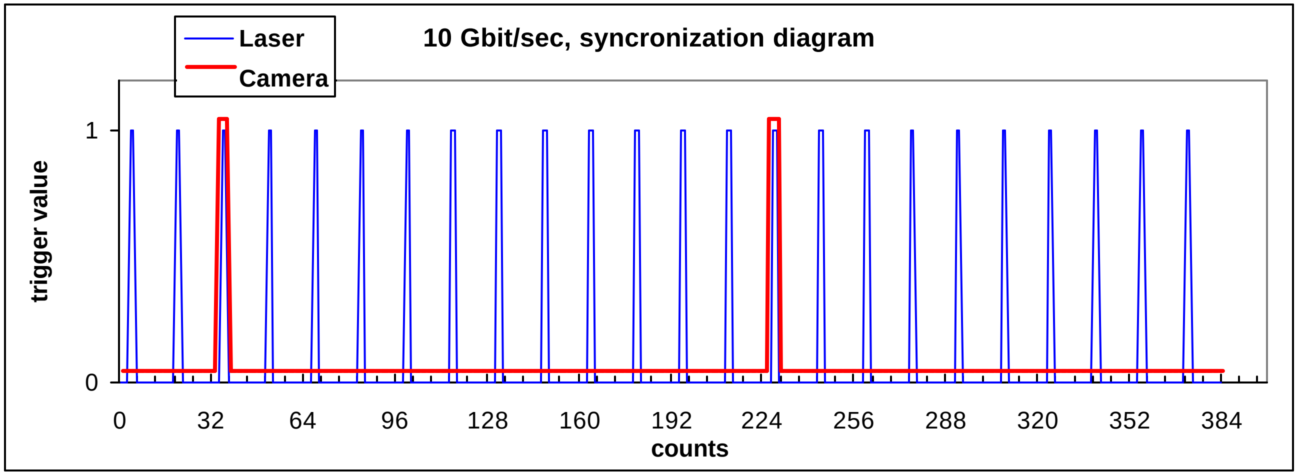
Ultra-high transfer rate demonstration (laser pulse energy consideration)



- Pulse energy decreases with repetition rate for *f* > 1 kHz (weaker signal at higher rate (LightWave Electronics 210G, doubled Nd:YAG laser).
- Required diffraction efficiency (due to scatter rather than signal strength limitations) allows hologram readout even at faster rates (upto 10kHz).

10 Gbit/sec readout timing diagram (4/00 and 9/00)



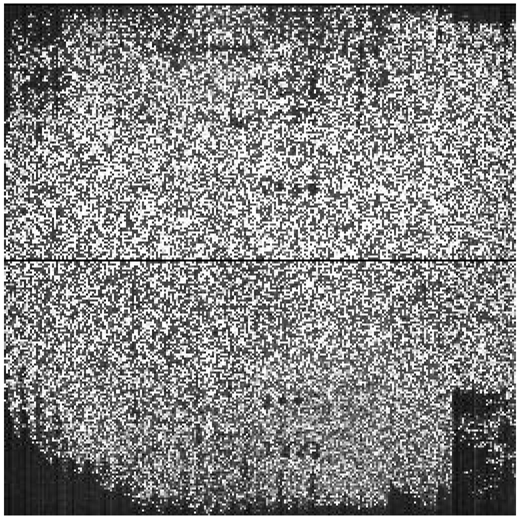


- Laser trigger frequency:
  every 8 counts;
- Camera trigger frequency:
  every 96 counts;
- Camera width:
  2 counts (50 μsec).

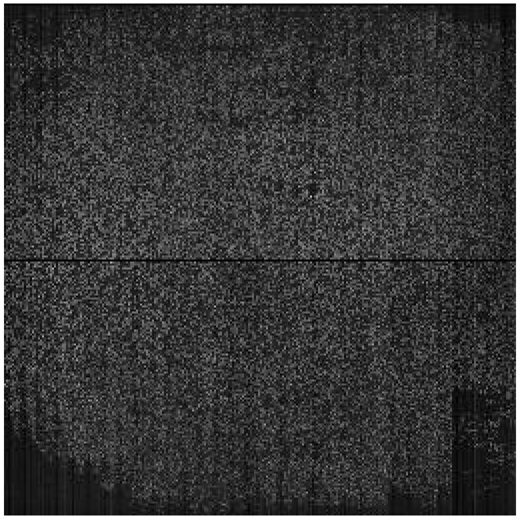
10 Gbit/sec transfer rate demonstration

- Page capacity = **68.5 Kbytes** (user);
- Holograms incrementally recorded at 300 RPM disk rotation speed;
- Material: 200 μm thick Polaroid ULSH-500, 6.5” dia disk;
- Holograms retrieved at **10 Gbit/sec (10,000 fps),**
- Camera and electronics sampled holograms at ~1 Gbit/sec (every 12th image, camera integration window = 25 μsec),
- Data captured with logic analyzer;
- Images uploaded from decoder boards memory to verify raw error rate (~ 1%).

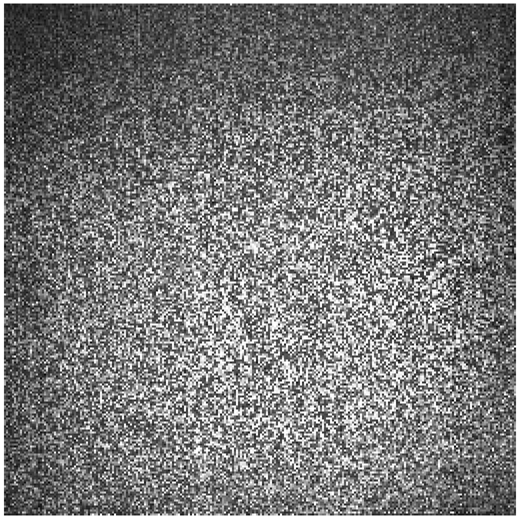
Holograms read out at > 1Gbit/s optical transfer rate



• 1 Gbps (0.8% raw Byte errors);



• 6 Gbps (~ 1% raw Byte errors)

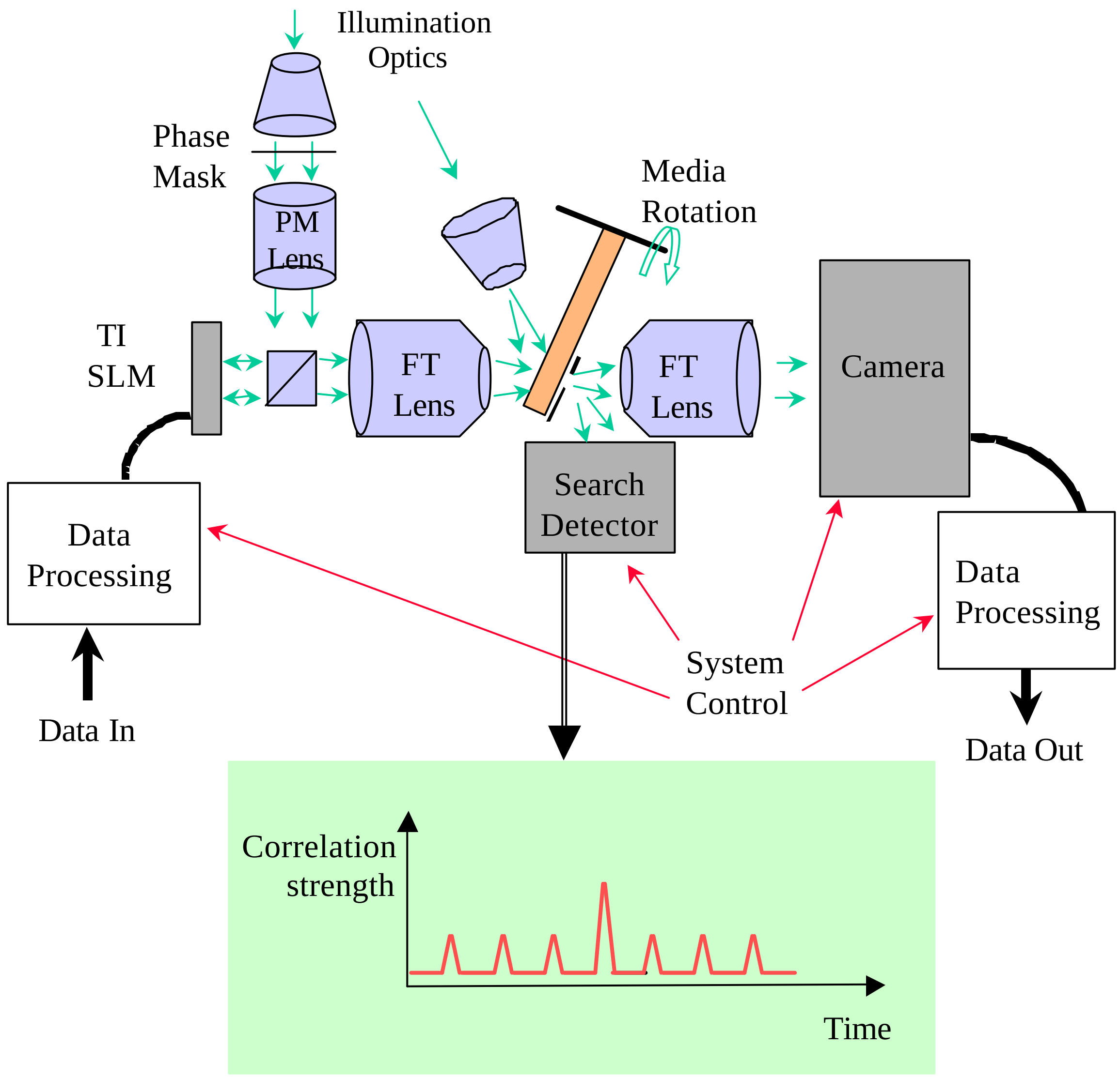


• 10 Gbps (~1.5% raw Byte errors);

• different set of optics: higher optical efficiency than 1 and 6 Gbit/sec.

Material: 200 μm and 500 μm thick CROP photopolymer, thermally precured.

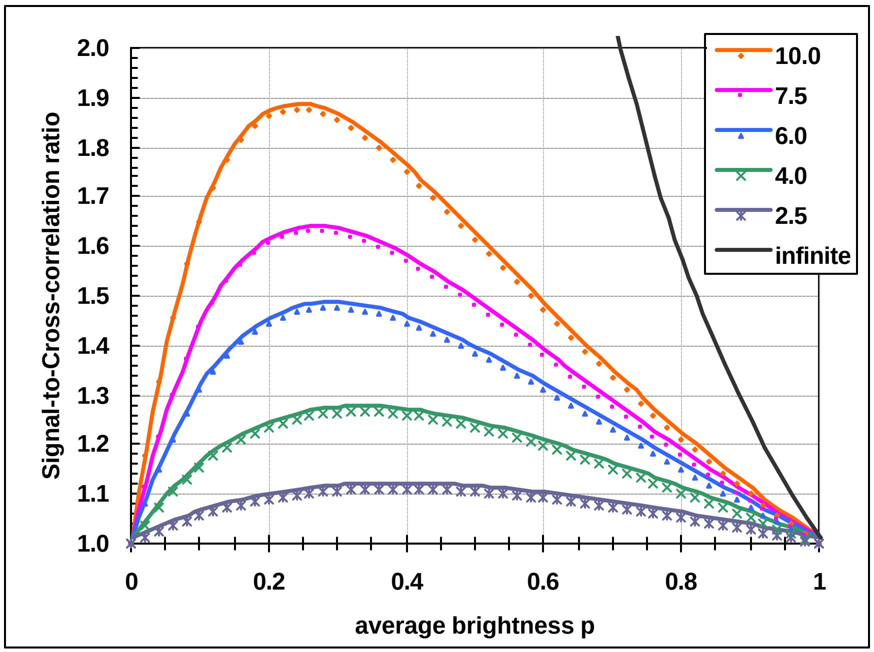
Search in rotating holographic disk system

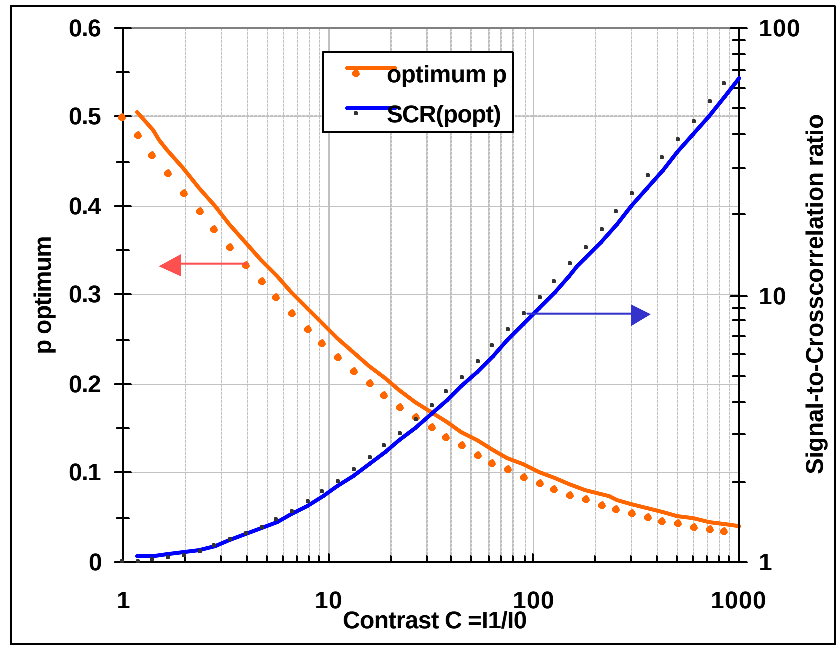


Auto-and cross- correlation for binary images
(amplitude modulation / confocal detection)

SLM contrast: $C = I_{“1”} / I_{“0”}$

p **- average number of 1’s.**





$$SCR = \frac{\langle signal \rangle}{\langle crosscorrelation \rangle} = \frac{[p(C-1)+1]^2}{[p(\sqrt{C}-1)+1]^4}$$

$$\left.\frac{\langle signal \rangle}{\langle crosscorrelation \rangle}\right|_{p=p_{optimum}} = \frac{(C-1)^4}{16C(\sqrt{C}-1)^4}$$

$$p_{optimum} = \frac{1}{\sqrt{C}-1} - \frac{2}{C-1}$$

$$C \to \infty,\ p_{optimum} \to 0$$

$$C \to 1,\ p_{optimum} \to 0.5$$

- **SLM contrast is a crucial parameter;**
- **For typical FLC *C*~ 5 to 8 => SCR ~1.5 at best.**
- **Stronger signal at higher *p.***

Summary

- **1 Gbit/sec end-to-end demonstration in holographic disk system;**
- **Hardware implemented holographic channel decoding, deconvolution, and Reed-Solomon ECC electronics;**
- **10 Gbit/sec sustained optical transfer rate from a holographic disk system demonstrated (**end-to-end operation possible with faster camera, e.g., CMOS, and new HDSS electronics**);**
- **Density: ~ 10 bits/μm^2 (at 1 to 10 Gbit/sec transfer rate);**
- **Higher bit density at present data rate is possible in reduced scatter materials.**
- **Potential application for relational data base search.**

- Acknowledgements: **DARPA/NSIC HDSS Consortium (systems);**
DARPA/NSIC PRISM Consortium (materials).