Multi-layer Optical Data Storage Based on Two-photon Recordable Fluorescent Disk Media

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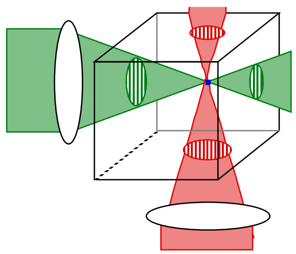
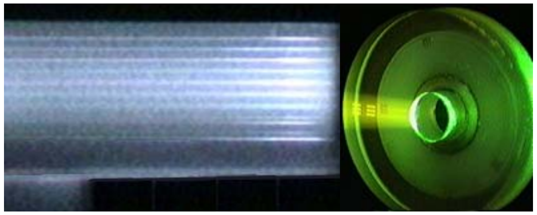


- **Introduction**
- Recording methods and systems
- Signal Readout
- Summary



Multi-layer Optical Storage for Mass storage

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Internet and Data Warehousing are demanding:

Tape equivalent disk drive with low media cost, high media volumetric density (100-500GB/disk, <100ms access, >100Mb/s data rate)

Currently magnetic disk drive and optical disk drive are having difficulties to further boost the data capacity, and no apparent low cost technical solution to $>100 Gb/in^2$ areal data density.

Opportunity for new technology

Multi-layer optical storage has higher data capacity and data rate potentials, Plus:

- Optical disk is removable, excellent for content distribution;
- Optical disk drive can random access data.
- Optical storage has good data life time.

Emerging Technologies

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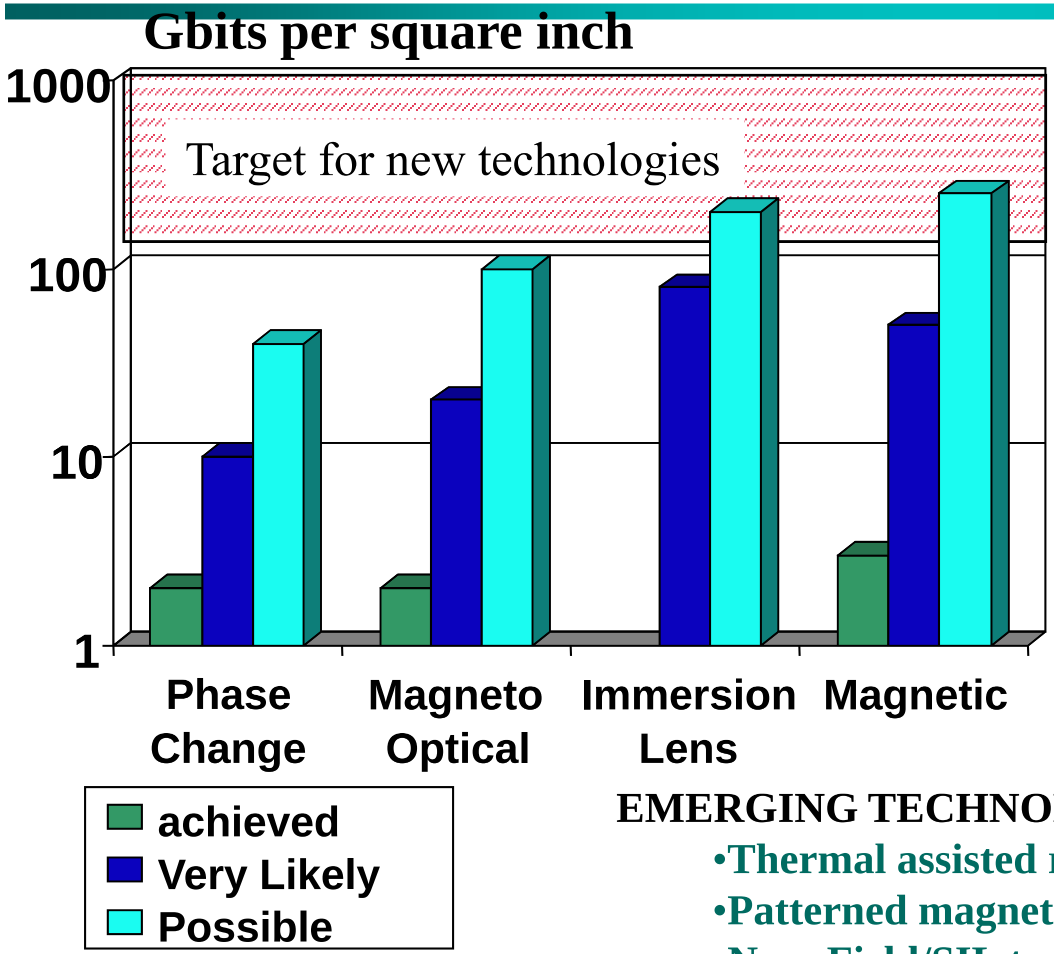

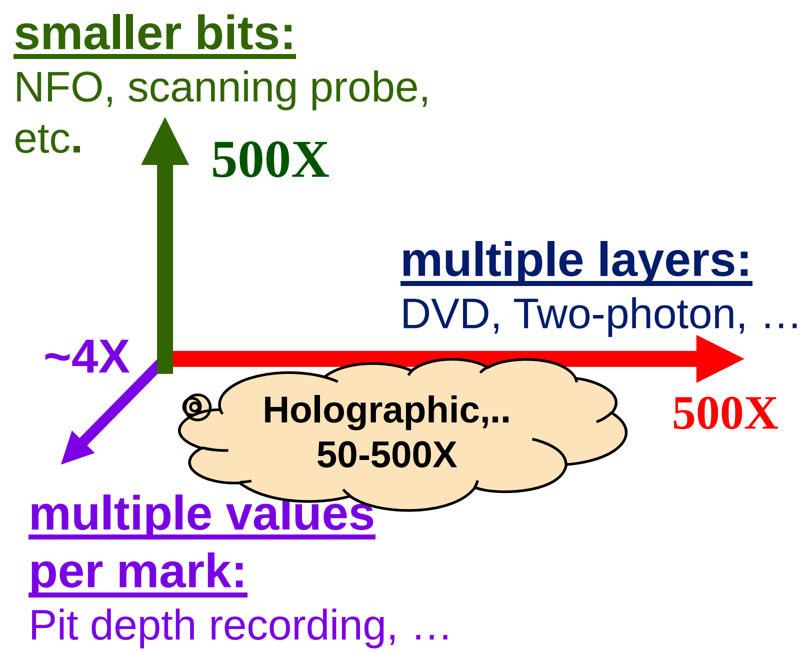

EMERGING TECHNOLOGIES

- Thermal assisted recording on high K_v materials
- Patterned magnetic media
- Near Field/SIL techniques on MO
- Multi-layer disks and cards
- Holographic disk storage
- Probe disk storage
- Nanometer controlled ROM replication

Two-Photon Recorded Multi-layer Optical Disk

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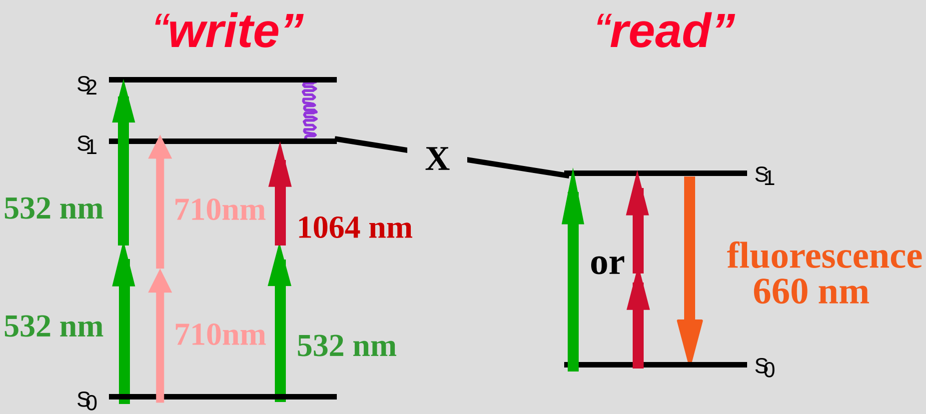
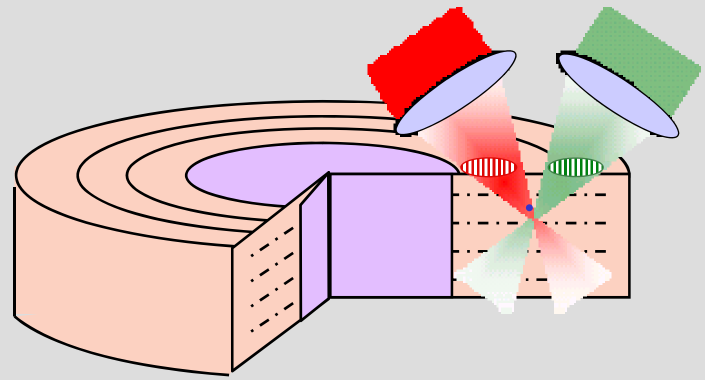
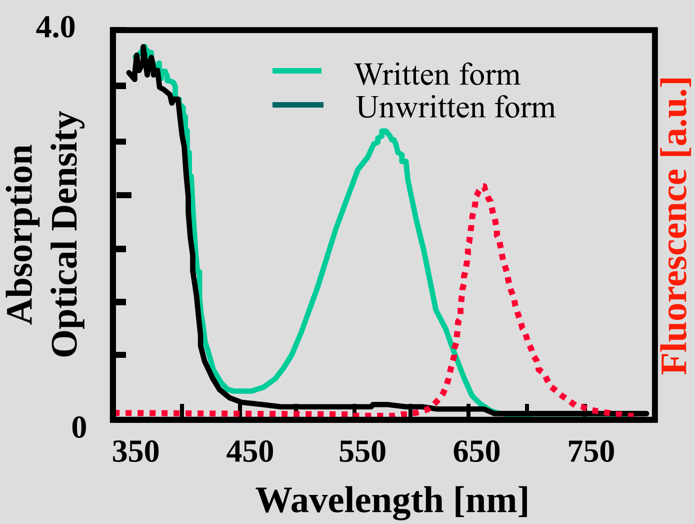
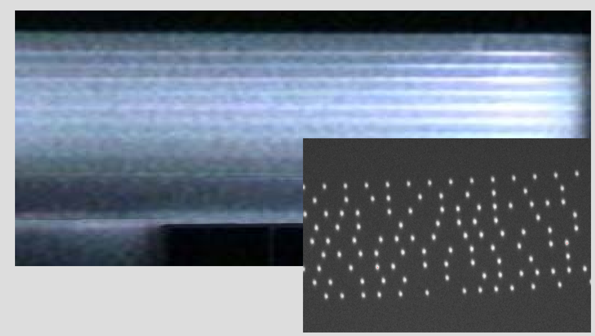




- Excellent volumetric control
- Readout by fluorescence
- Broad write/read λ-tolerance

- Single or multiple beam gated recording
- Very closely spaced layers
- Potential for parallel readout





- Low cost moldable plastics
- Ultra high density media

Potential Data Capacity of Two-Photon Recorded Multi-layer Disk

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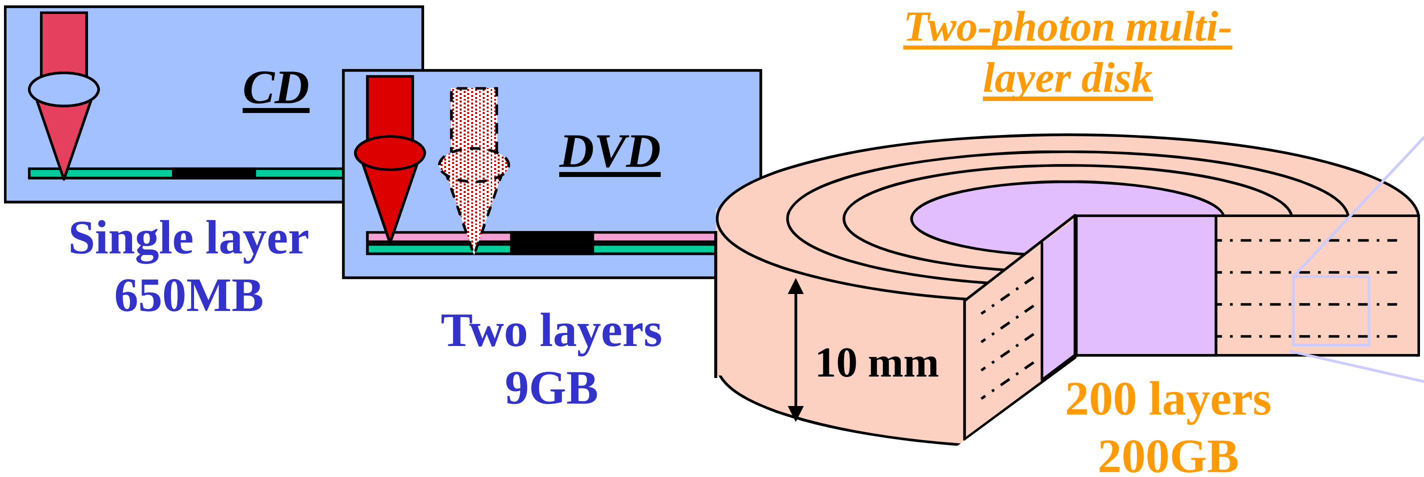

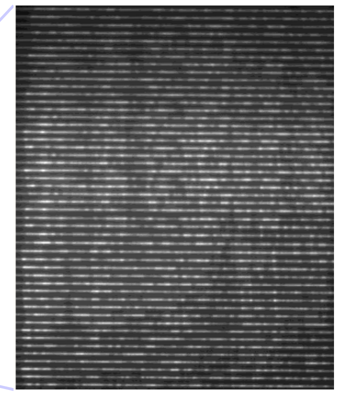

DVD

Layer pitch = 40-70 μm
λ = 635-650 nm
NA = 0.6
Spot size= 1.22 λ /NA =1.3 μm
# layers= 2
Capacity = 8.5 GB

Two-photon multi-layer disk

Layer pitch = 50 μm
λ = (532nm) / 600nm (write)/read
NA = 0.35
Spot size = 1.22 λ /NA= 1.8 μm
# layers = 200
Capacity = 200 GB

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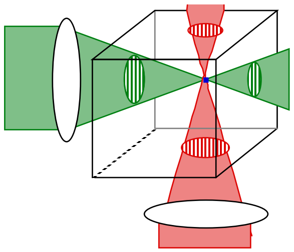

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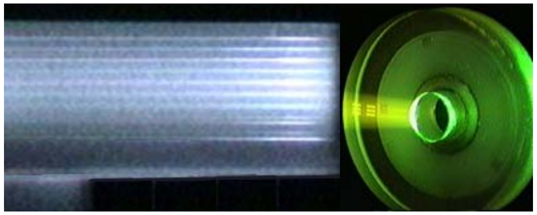

Two-photon Recording Methods

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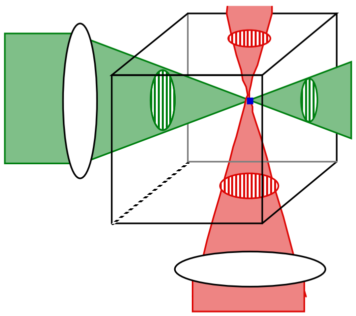
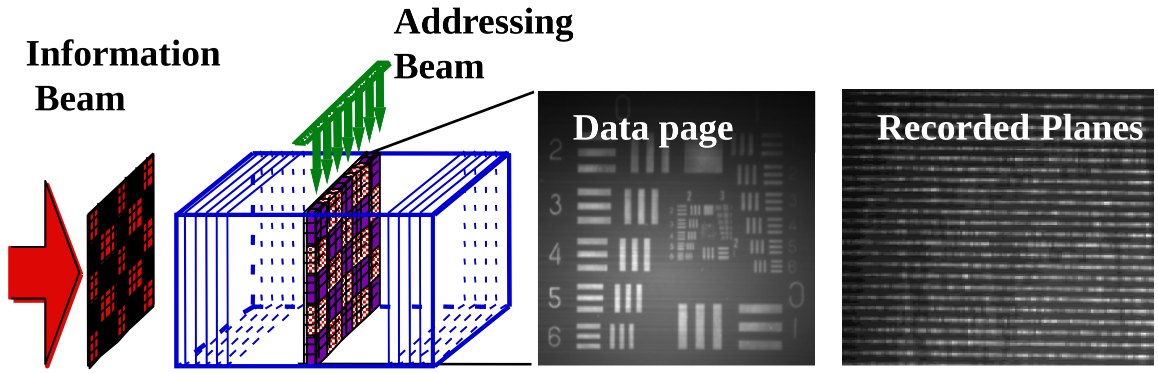
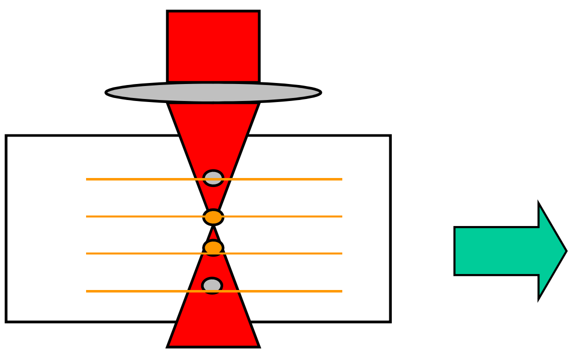
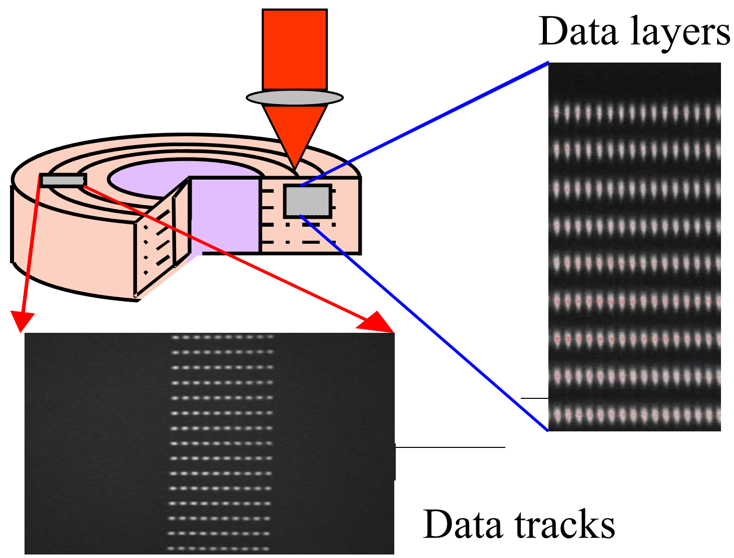




Two-beam recording



Single-beam recording



Two-beam Two-photon Recording System

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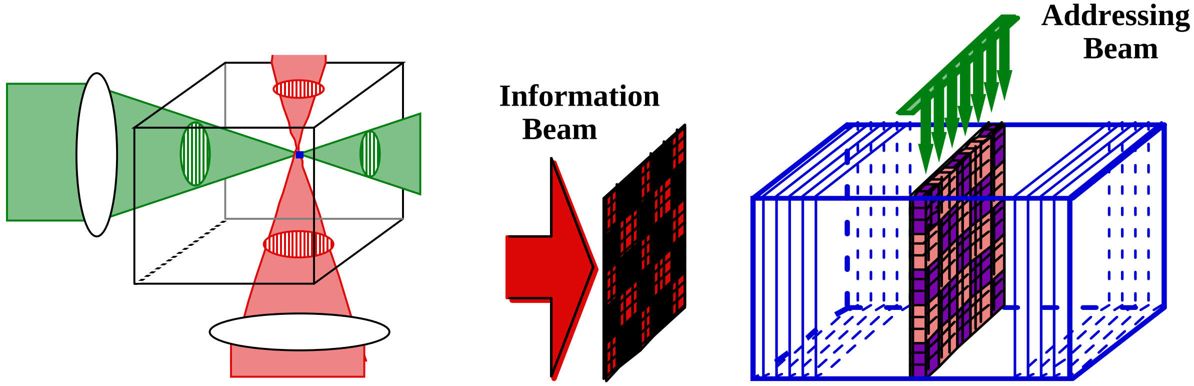

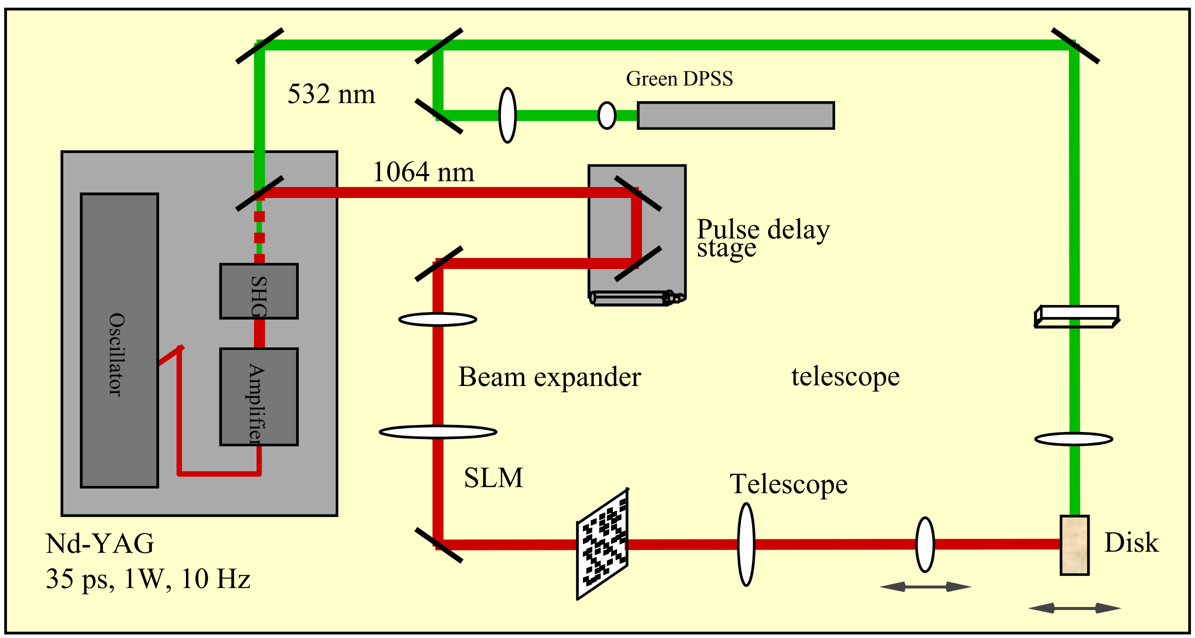

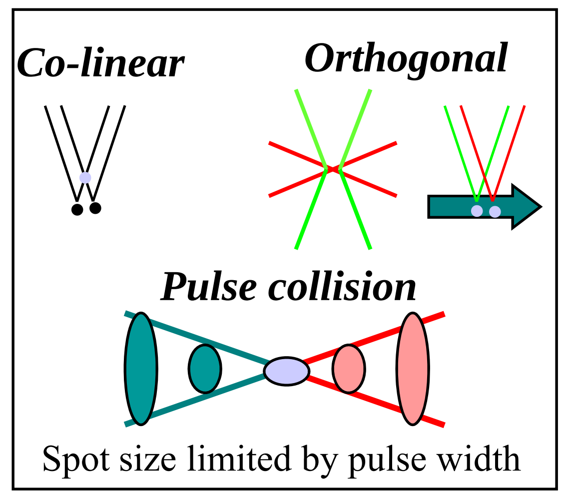

Two-beam Two-photon Recording Setup and Experimental Results

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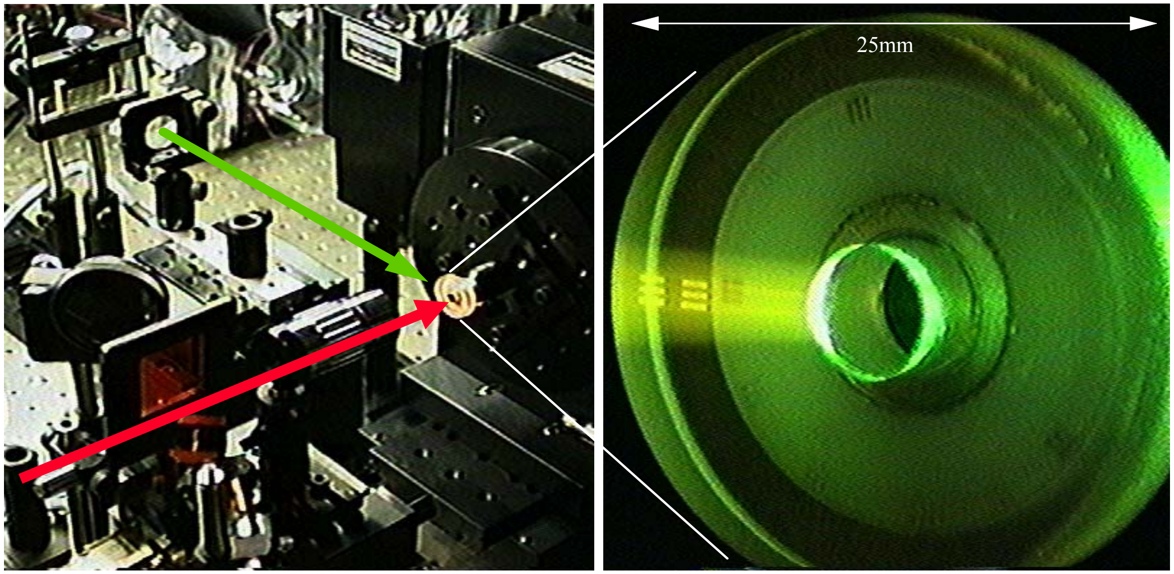
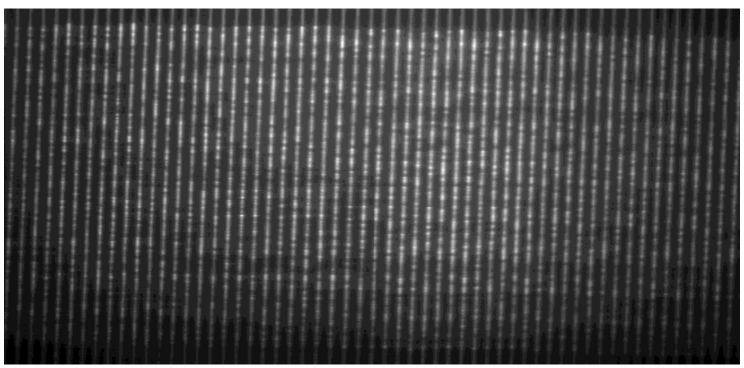
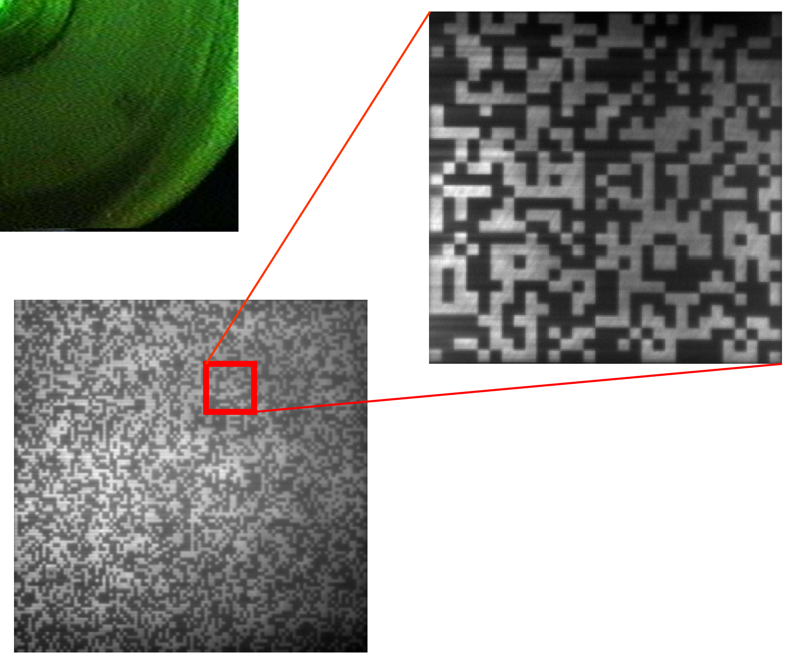




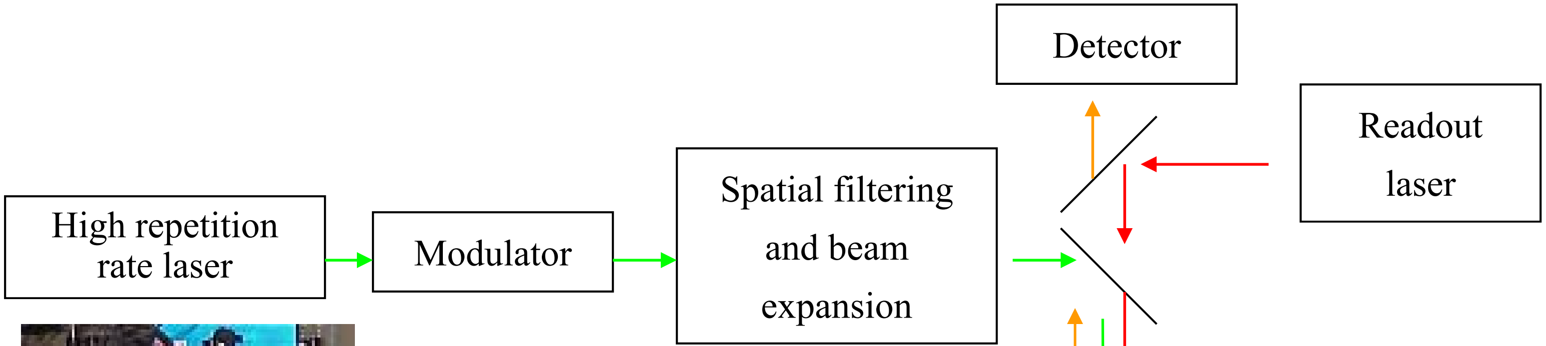
< 80 µm plane pitch

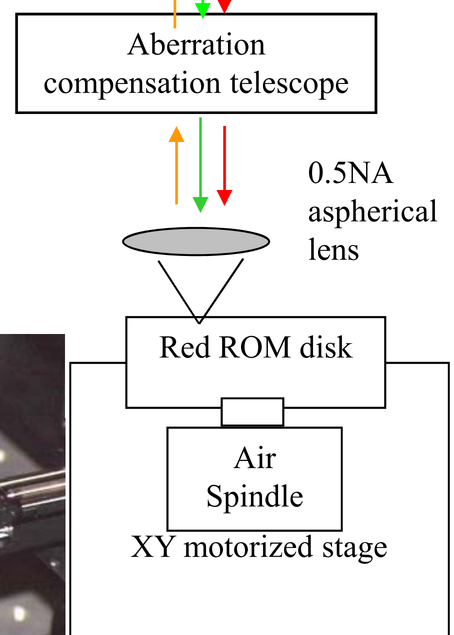
Binary pattern

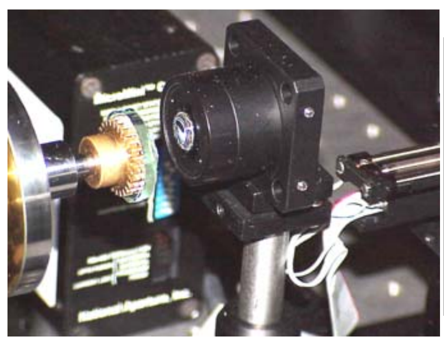


< 5x5 μm^2 bits

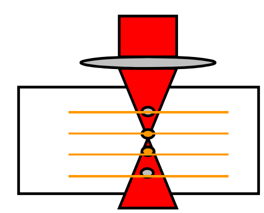
Single-beam Recording Setup







Nd:Vanadate (model locking)
532nm, 27MHz, 6.5pSec,
5W (average power)



Single-beam Recording vs. Two-beam Recording

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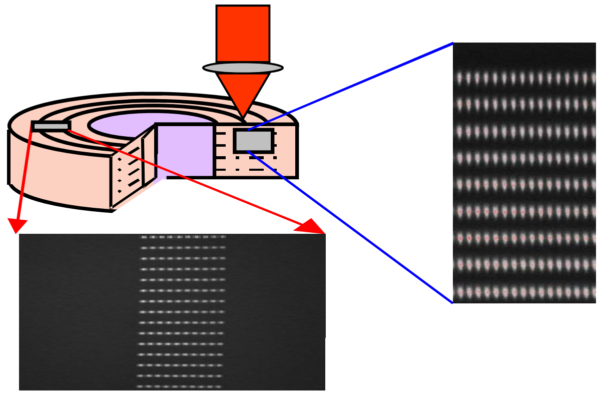
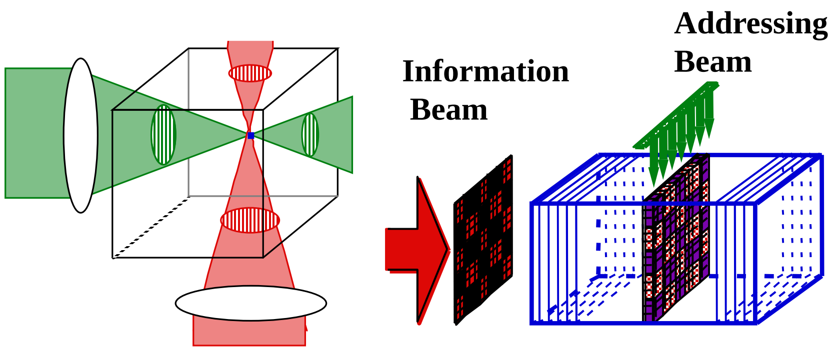
Single-beam two-photon recording system



- Bit oriented
- Easy alignment
- Less complexity
- Suitable for high repetition rate laser

Two-beam two-photon recording system



- Page oriented
- Large scale SLM
- Suitable for high peak power and low repetition rate laser

Recorded Bit Geometry with Single-beam Recording

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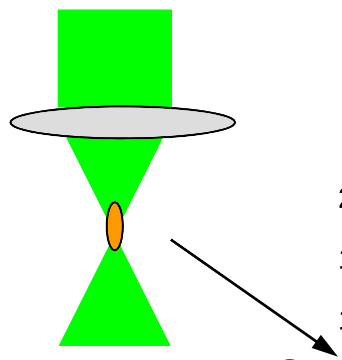
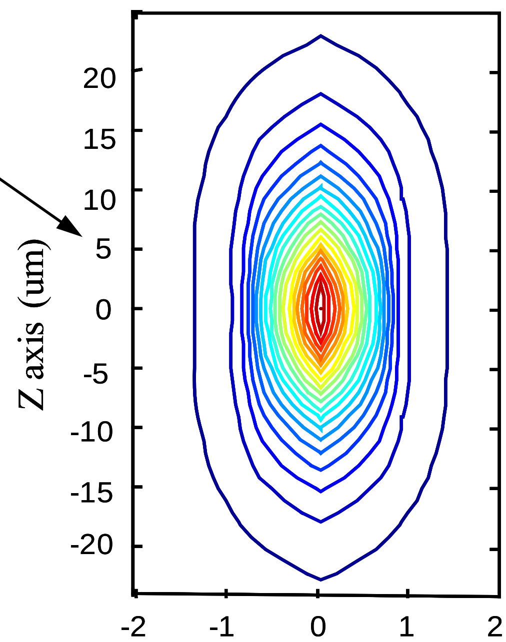
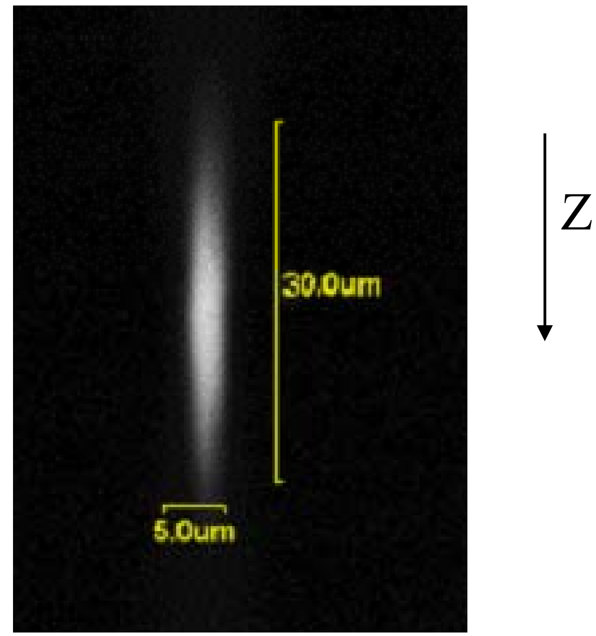


Simulation of the recorded bit geometry based on **intensity square** of gauss beam at the focus.





Confocal scan image

Layer Separation vs. NA of Recording Optics

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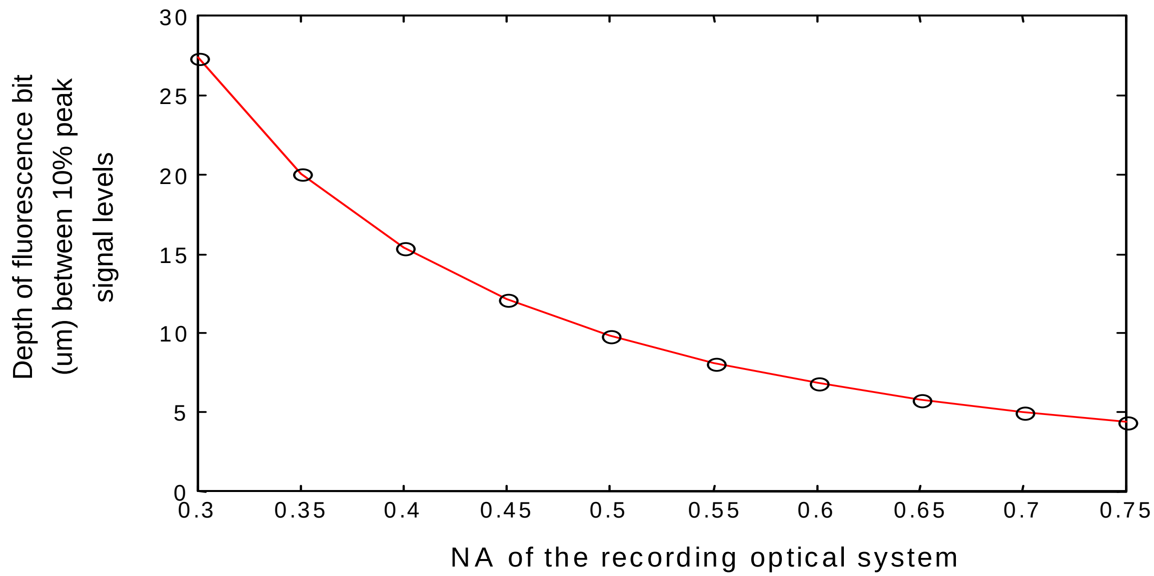
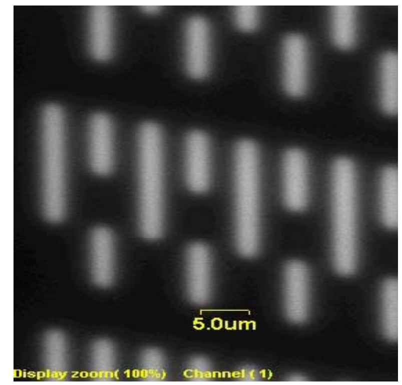
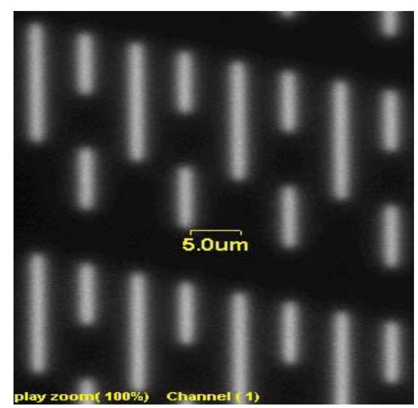


0.35NA (XY scan image)
1.9 µm@ 50% peak level



0.75NA (XY scan image)
1.1µm@50% peak level



0.75NA (Depth scan) **0.35NA (Depth scan)**

Z

Recording Speed and Recording Lasers

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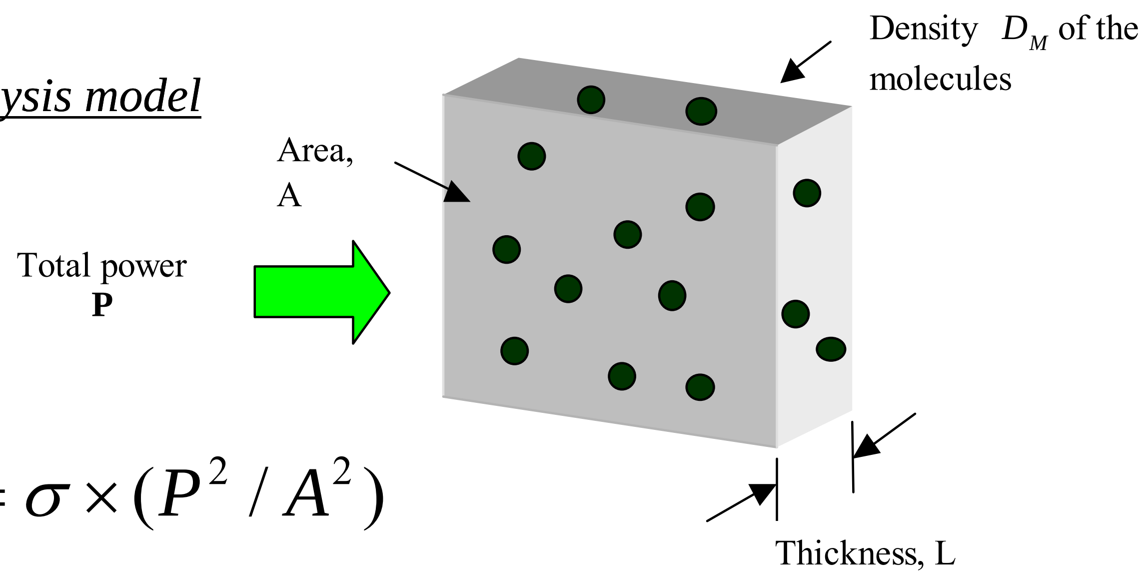
Two-photon absorption analysis model



General description:

$$\Delta P'_{abs} = \sigma \times I^2 = \sigma \times (P^2 / A^2)$$

σ two-photon cross section.

Recording with pulse laser:

$$V_r \propto D_M L\left(\frac{\sigma \times N_p^{\ 2} f_{rep} \hbar\omega}{2t_p A}\right)$$

t_p laser pulse width, N_p number of photos per laser pulse, f_{rep} laser repetition rate

Recording Lasers and Achievable Recording Speed

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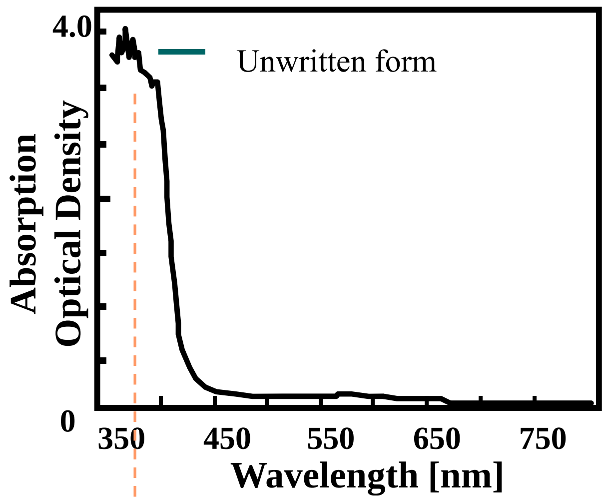
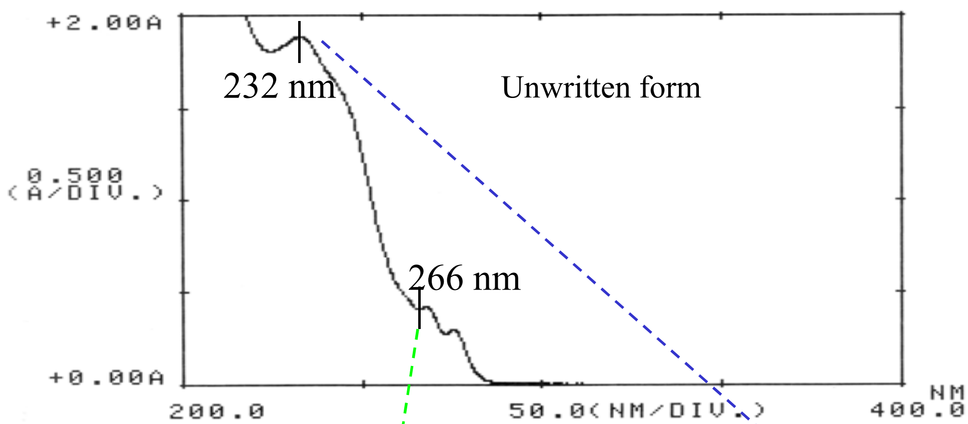
WORM Media I



WORM Media II



Ti:Sapphire laser (Mira)
710nm, 76MHz, 200fs,
400mW(average power)

Nd:Vanadate (model locking)
532nm, 27MHz, 6.5pSec,
5W (average power)

Mode-locking blue laser
with similar parameters
of Nd:Vandate

1Kbit/Sec
1999

>1Mbit/Sec
Now

>10Mbit/Sec (projection)
2003

Recording Lasers

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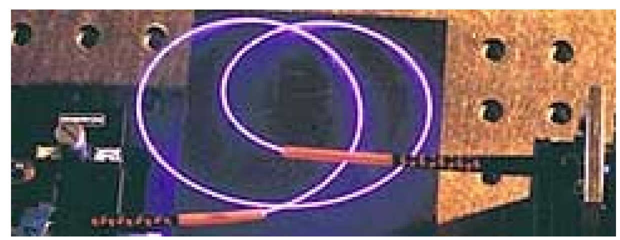
Ti:Sapphire 710nm

Nd:Vanadate (model locking), 532nm



Blue Thulium doped fiber laser

Potential *blue recording laser: Mode-locking Fiber laser*

Initial Recording with Low Power Blue Laser

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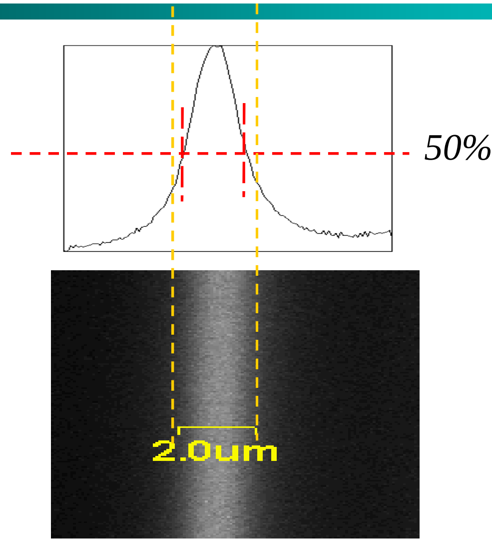
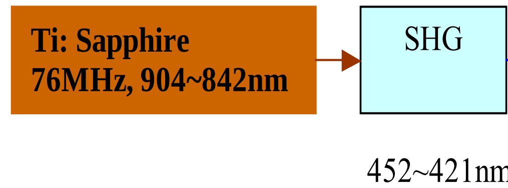
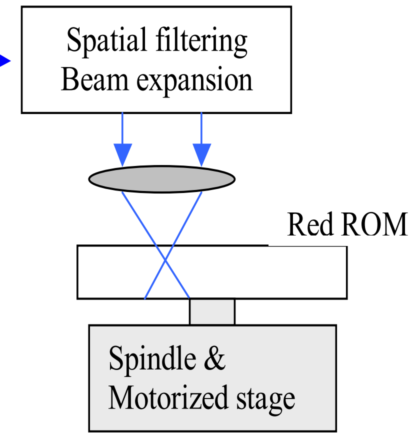
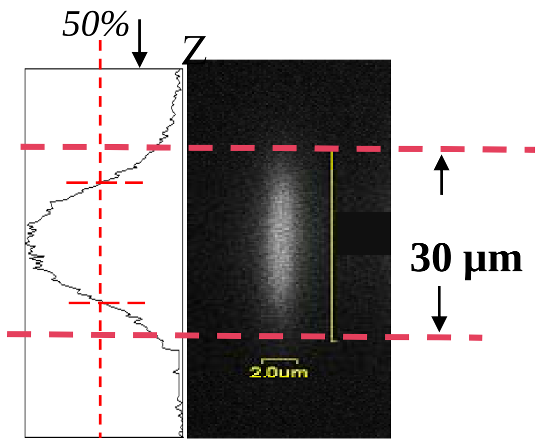


XY scan

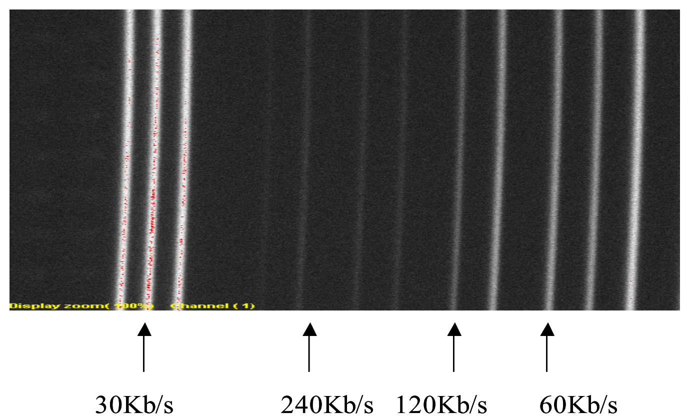




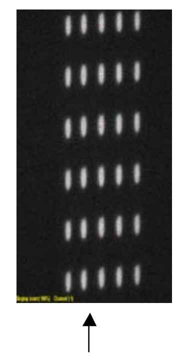
40mW average power
200fSec, 76MHz,
452~421nm



•**Smaller bit size**



452nm recording at different recording speeds



532nm recording
3W average power
500Kb/s

•**About 10X higher recording efficiency**

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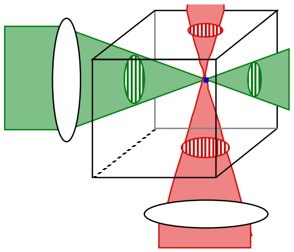

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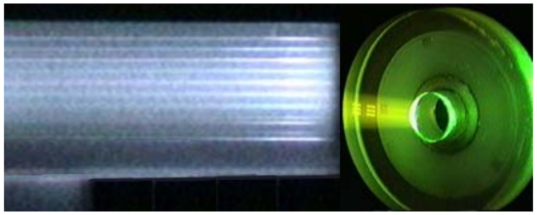

Signal Readout

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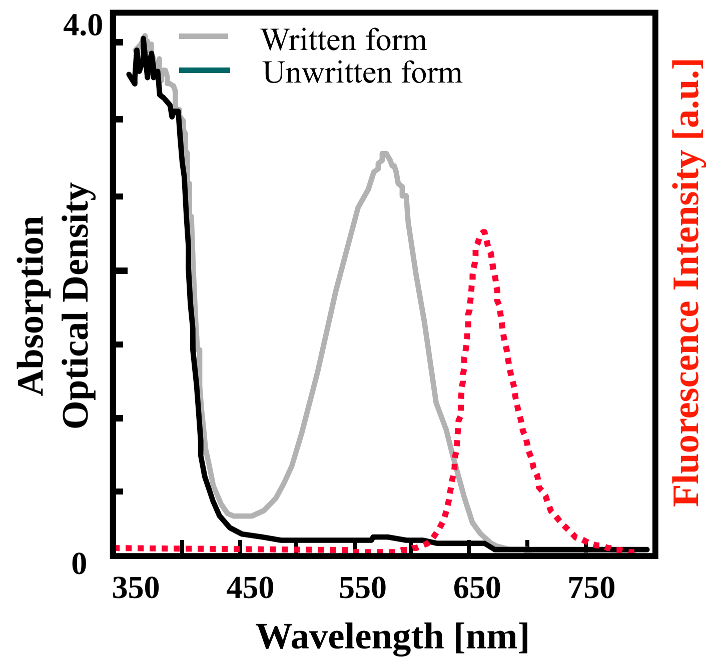
Recorded data bits will emit fluorescence once excited by readout laser beam.



Advantage:

- •Broadband readout laser wavelength
- •Incoherent fluorescence signal
- •Negligible index change
- •Non-reflective for readout laser beam

Disadvantages:

- •Low fluorescence level and low collection efficiency → High sensitivity detectors Photo Multiplier Tube (PMT), APD, custom designed detectors
- •Chromatic aberration

Signal Quality Measurement

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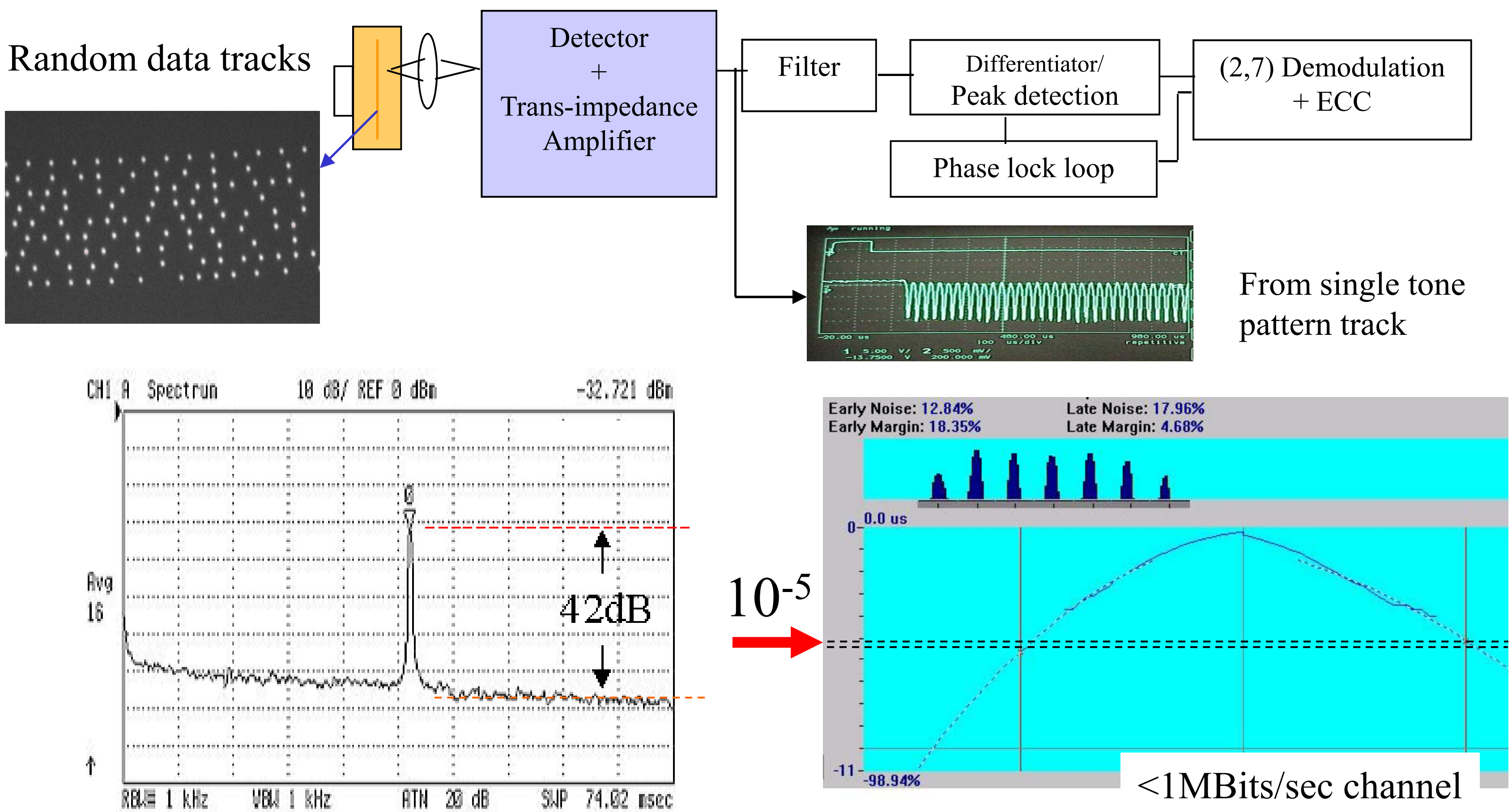

42dB CNR measured with $50KW/cm^2$ readout laser intensity and 20KV/A trans-impedance gain of amplifier

Spatial Filtering Controls the Layer crosstalk During Readout

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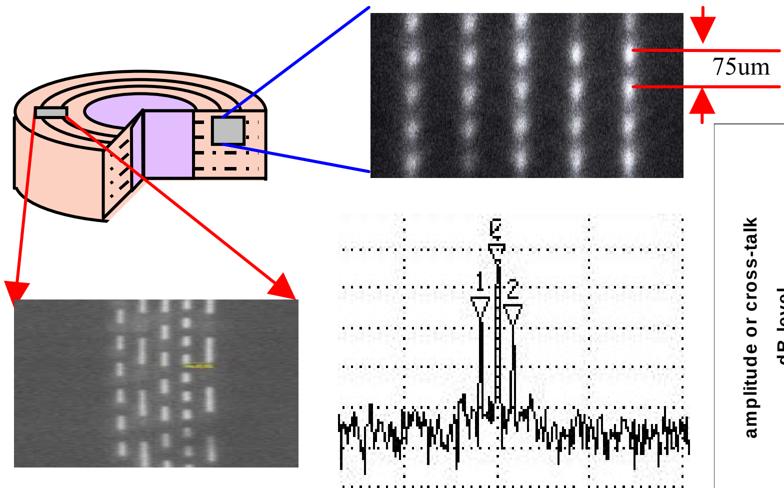
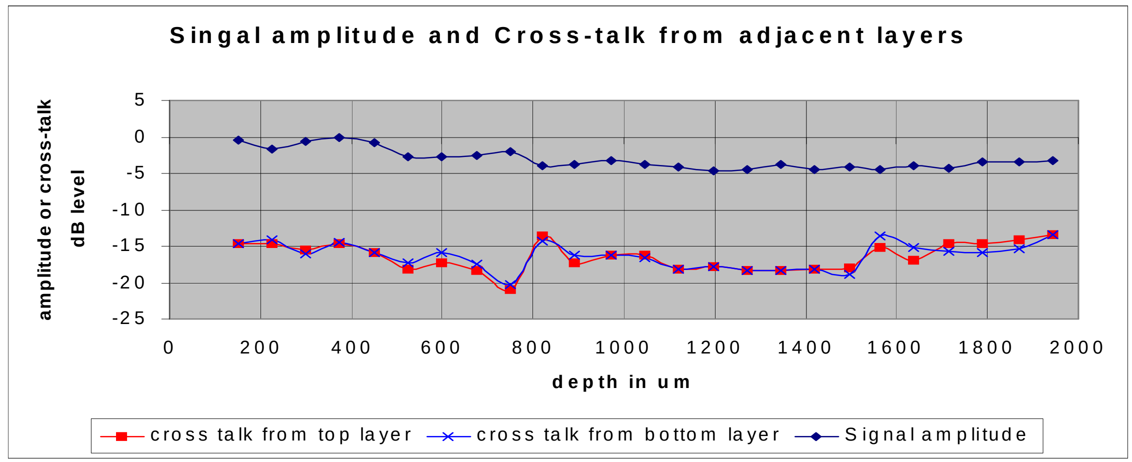
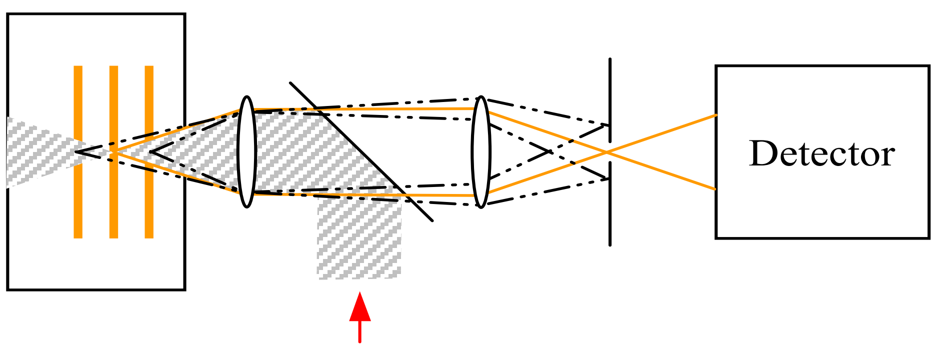
Layer crosstalk without spatial filting

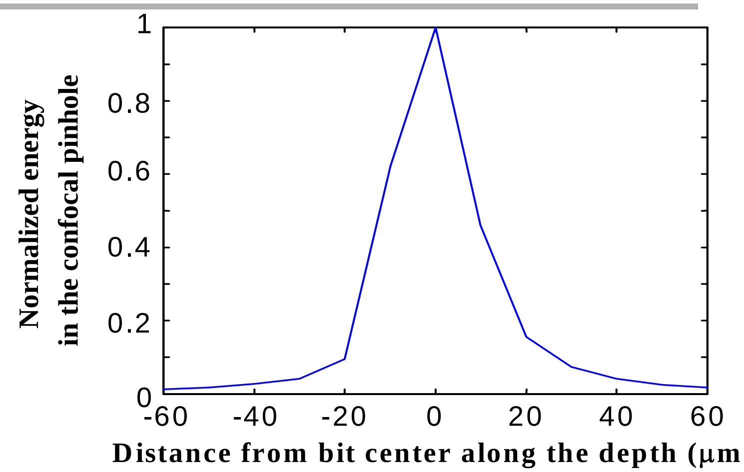
Layer crosstalk is critical during the readout. Experiment shows that no crosstalk accumulation when readout deeper layers



Signal spectrum







Servo During the Readout

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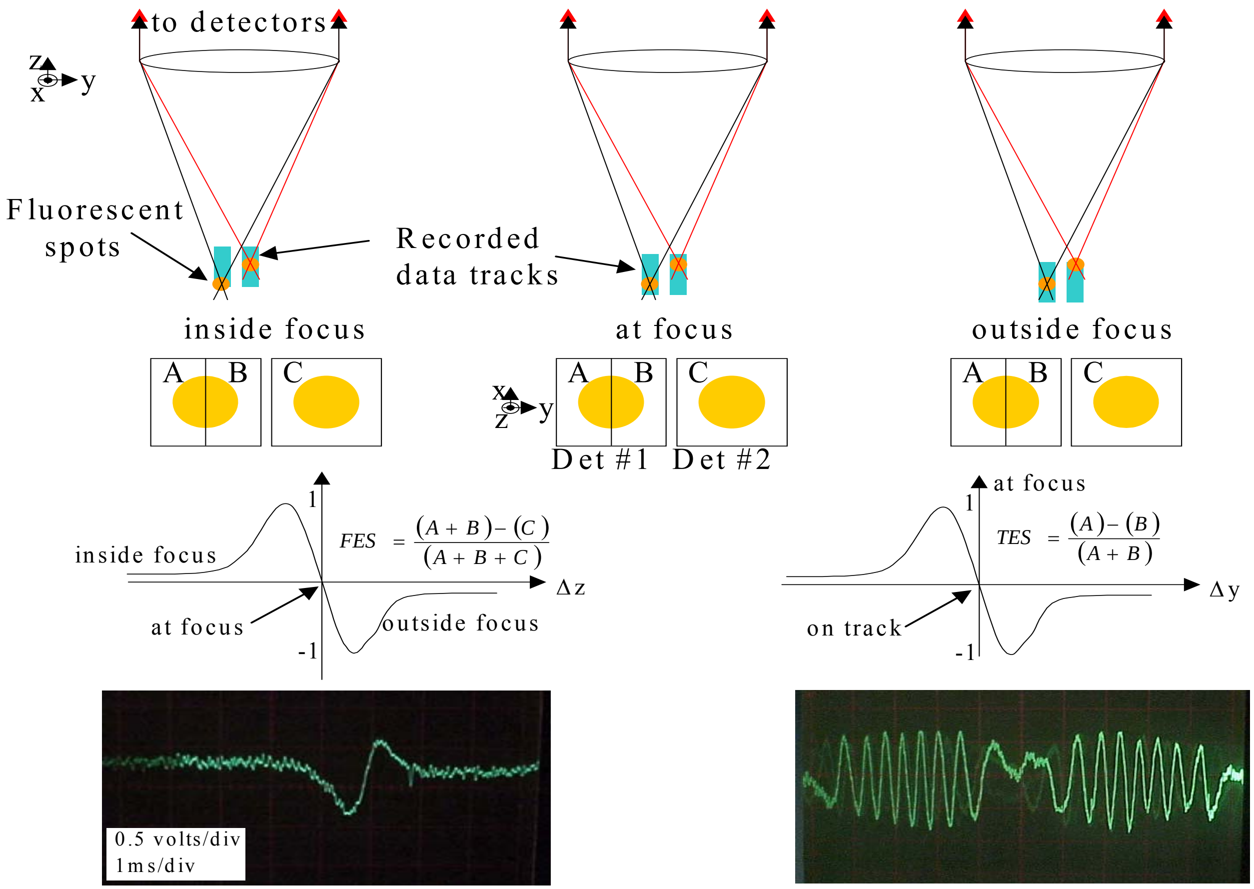
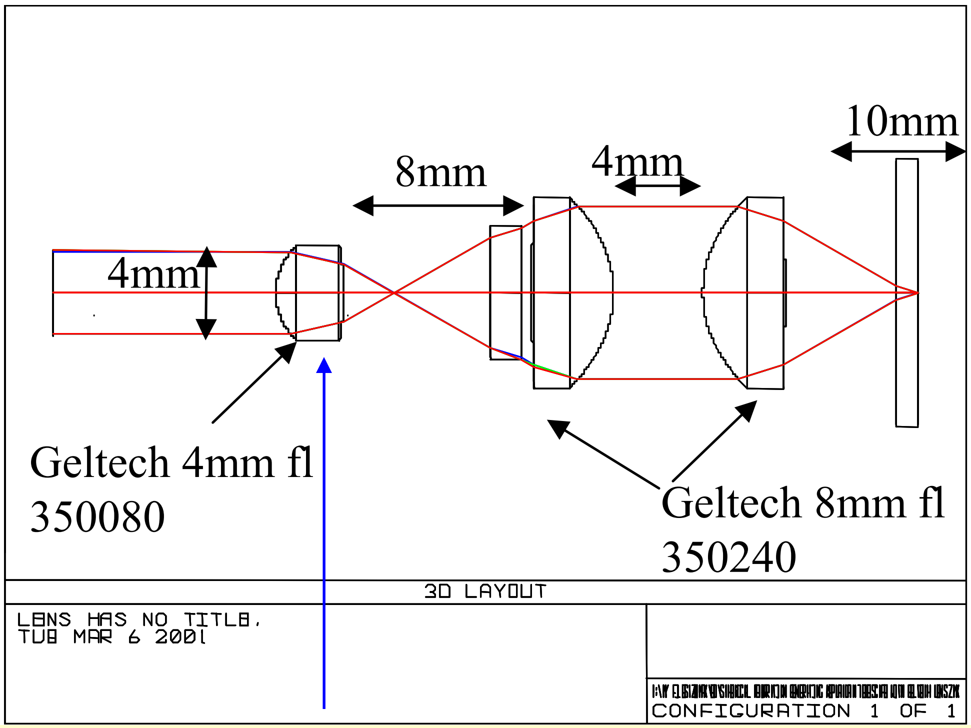


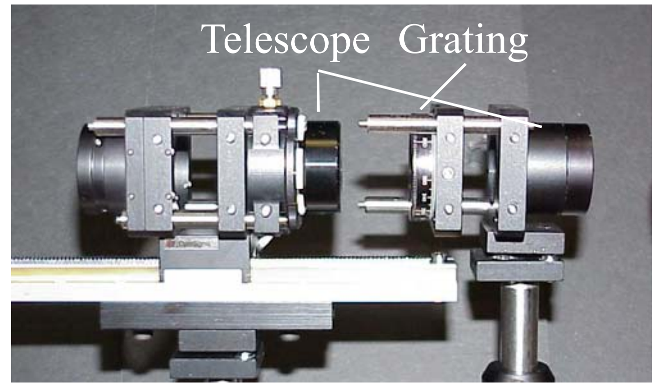
Tracking and focusing servo have been successfully demonstrated with described FES and TES generation methods.

Reference: E.P. Walker, X. Zheng, F.B. McCormick, H. Zhang, etc. Proceedings of SPIE, v.4090, pp. 179-84, 2000.

Aberration Compensation

Spherical aberration is the main source causing larger and lower intensity focus when readout and recording optics address different layer along the depth. By changing the beam conjugate entering the final objective lens, most of spherical aberration can be compensated.





Telescope used for in-plane parallel readout

Moving this lens axially from 0 – 1.32mm compensates 0 – 10mm of disk thickness (NA goes from 0.5 – 0.4), other compensation methods are under investigation

Telescope used for the recording

Data Stability

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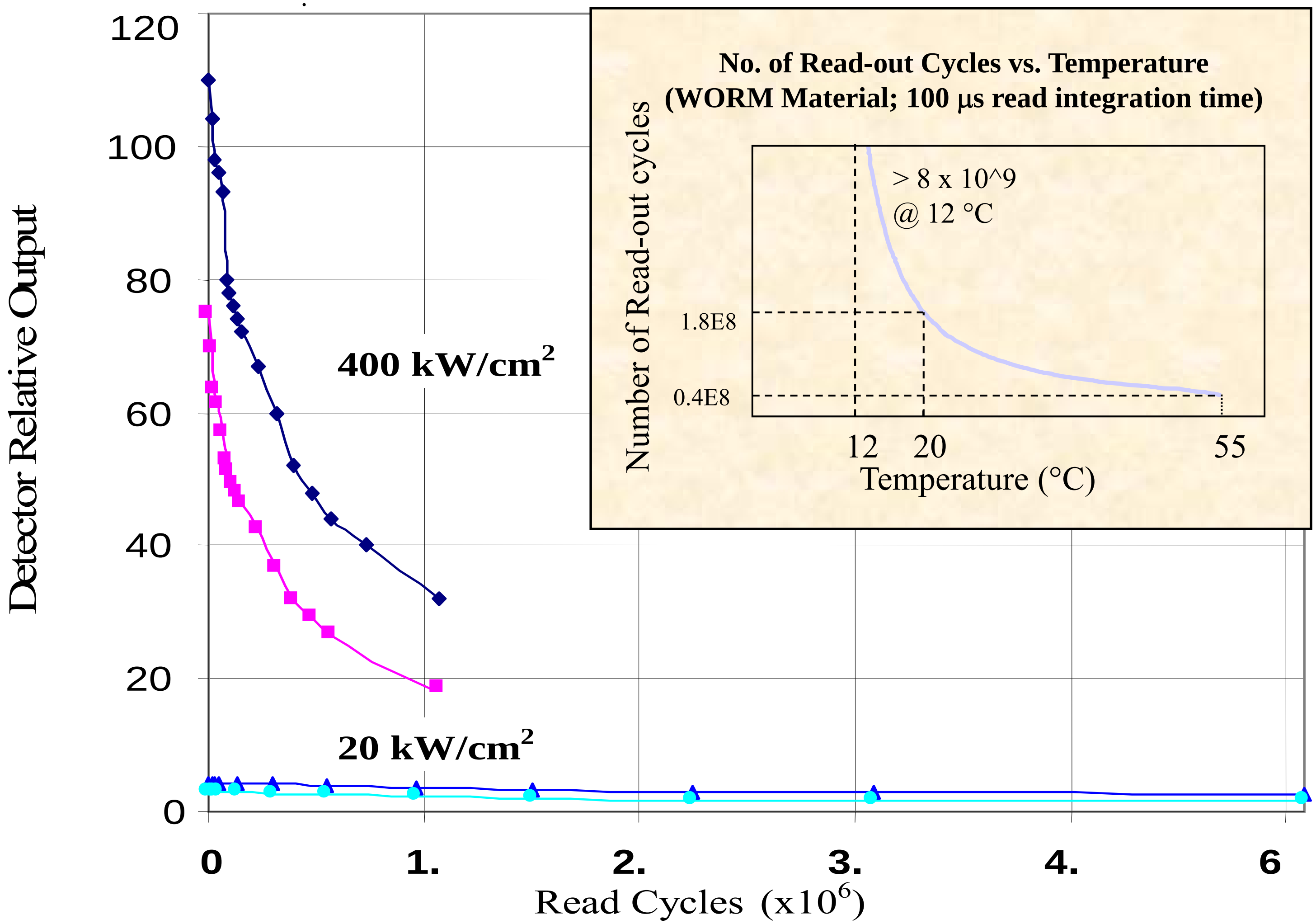
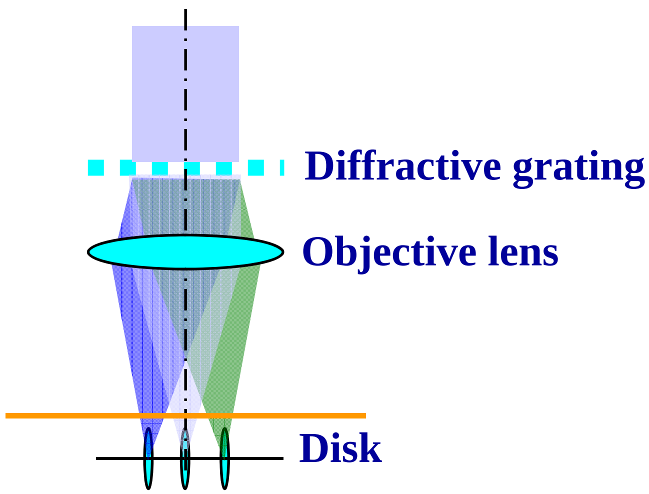
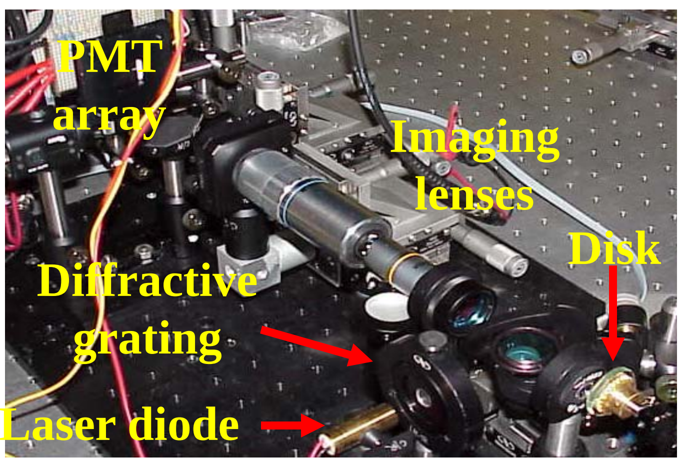
With normal readout laser power (<1mW), the written form read cycles exceeds 6 x 10^6.



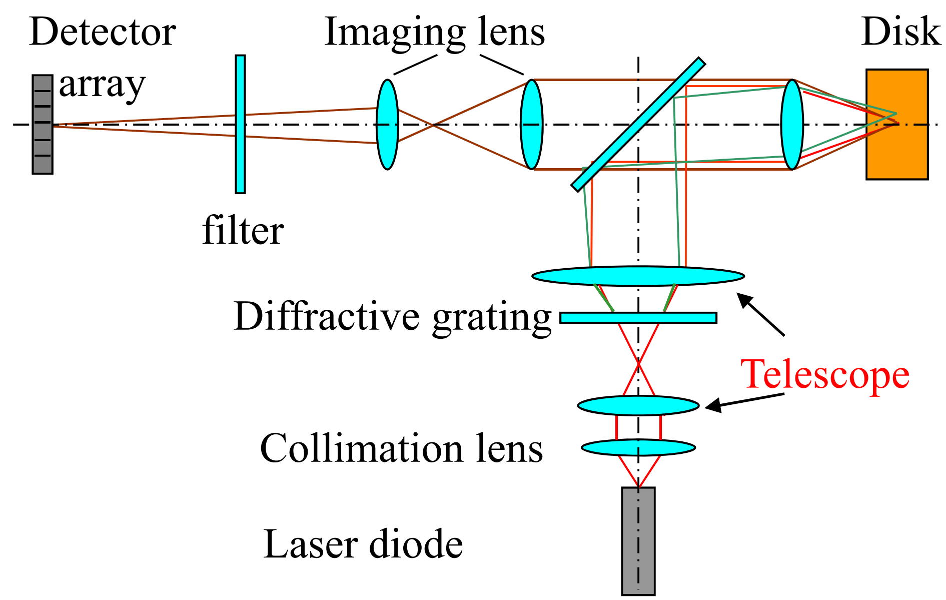
One Dimensional In-plane Parallel Readout

Using diffractive grating to generate an in-plane uniform spot array.

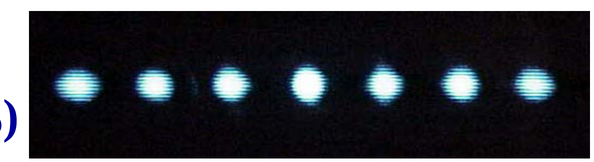




The telescope is added into the system for both spherical aberration compensation and spot pitch adjustment.



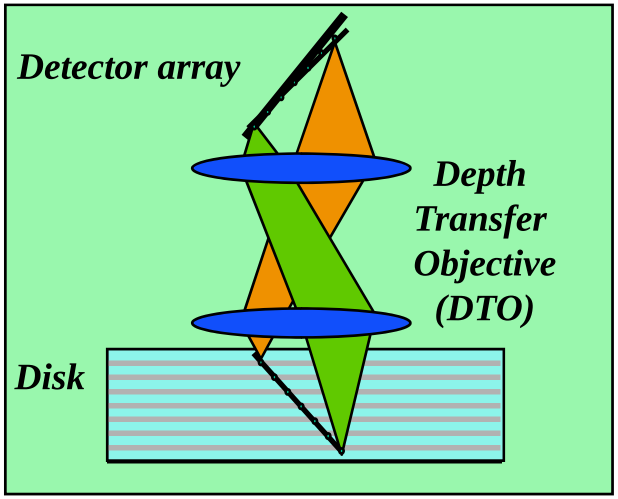
Spot array (power: ±10%)



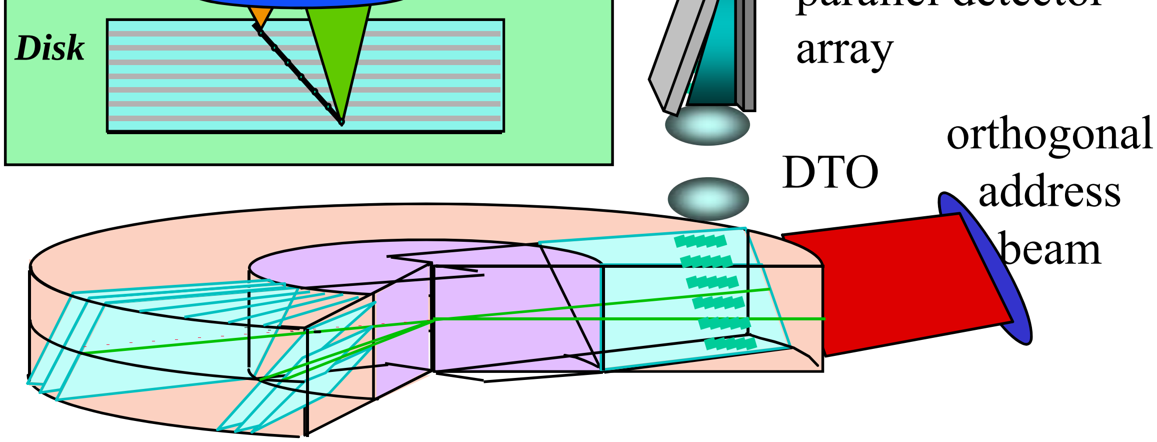
Parallel readout 7 channels of the data bits at a same depth by the collinear point-by point illumination. (in-plane parallel readout)

Two Dimensional In-depth Parallel Readout

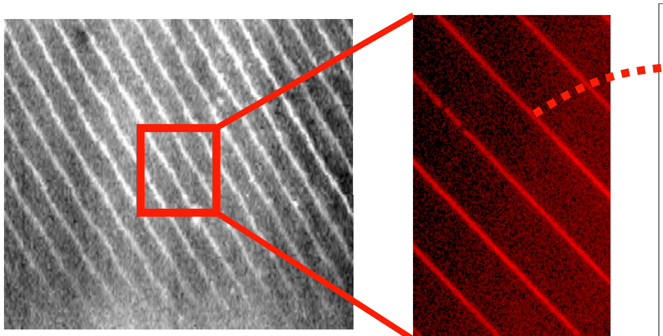
Call / Recall Inc.

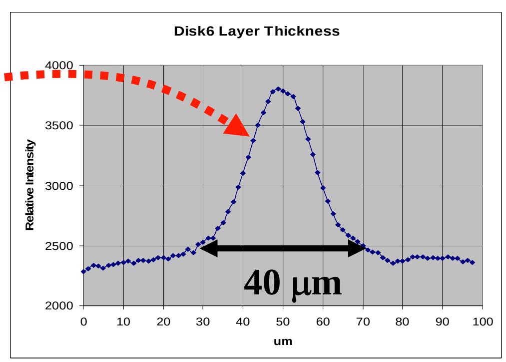


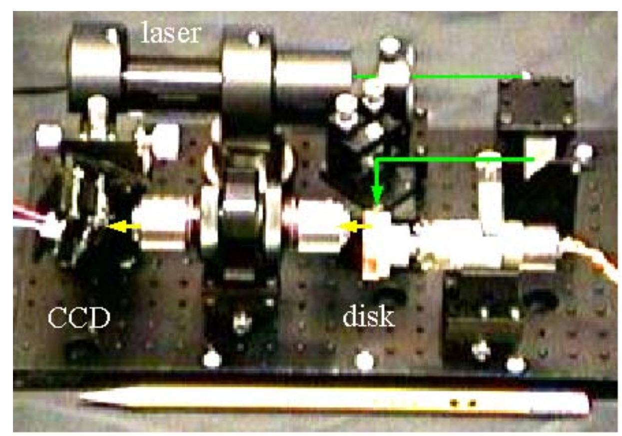
Orthogonal addressing method is only suitable for small diameter disks. Other illumination methods are under investigation.



- 25 mm diameter disk
- 6mm thick disk
- 120 “Turbofan” layers
- 400 µm layer separation
- Orthogonal illumination

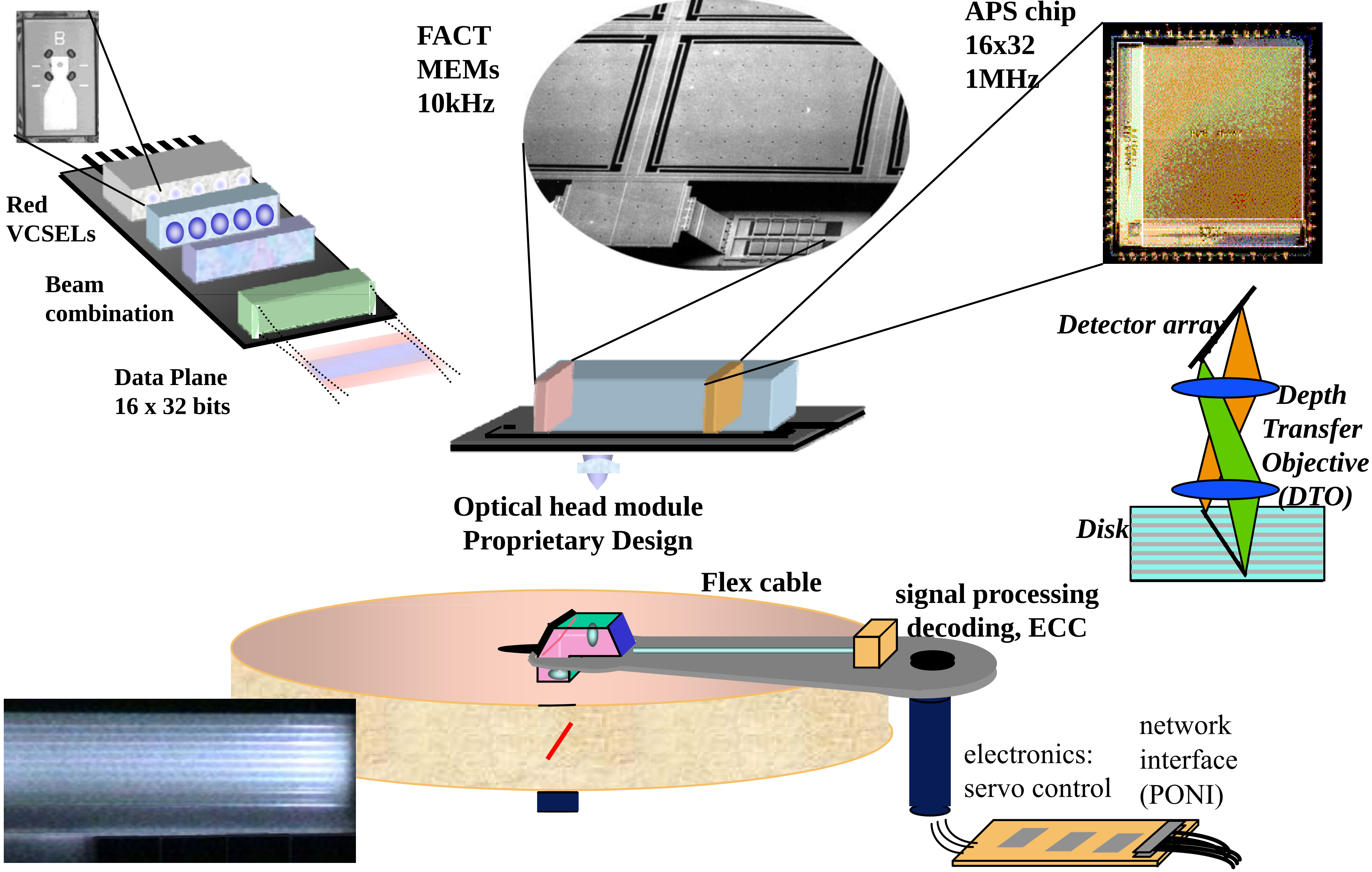






Fast Readout Optical Storage Technology (FROST)

Call / Recall Inc.



Summary

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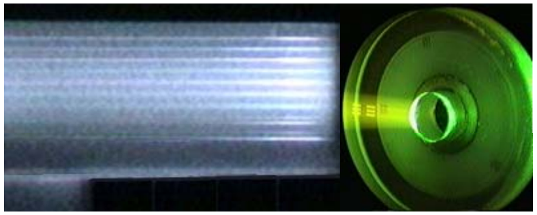
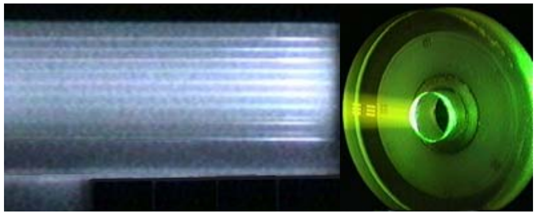
1. Two-photon recording (mainly single-beam recording method) has achieved under 2µm bit radial size and under 30µm bit depth.
2. Initial experiments show the feasibility to record 200 data layers into a 10mm thick disk.With larger NA optics and better aberration compensation, 200GB/disk data capacity is within reach.
3. Present Recording speed exceeds 1Mbits/Sec/channel.



Summary

Call / Recall Inc.

4. Fluorescence signal readout requires high sensitivity detectors, but readout signal quality is acceptable for channel speeds at 1Mb/Sec.
5. Bleaching of written bits during readout is minimized and a written bit can be read more than 10^6 times repeatedly without significant signal degradation.
6. Data read-out based on fluorescence without reflection, refraction or scattering from written bits enables parallel readout. Data read-out rates in excess of 360Mb/s using parallel channels should be within reach.



Multi-layer Optical Data Storage Based on Two-photon Recordable Fluorescent Disk Media

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Comparison to Disk Array System

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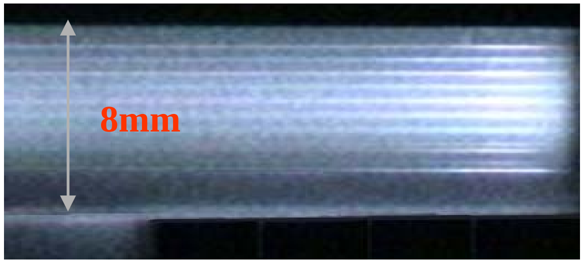

HDD or Disk Array

- Multiple disks-many heads
- non-removable disk
- low volumetric density

Multi-layer disk:

- Single readout head
- removable
- high volumetric density