

# ***High Performance Data Storage via Volume Holography***

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# Opportunity & Overview

## **Vision**

**InPhase's Tapestry™ technology will be the dominant choice for capturing, editing, archiving, distributing and securing digital image content.**

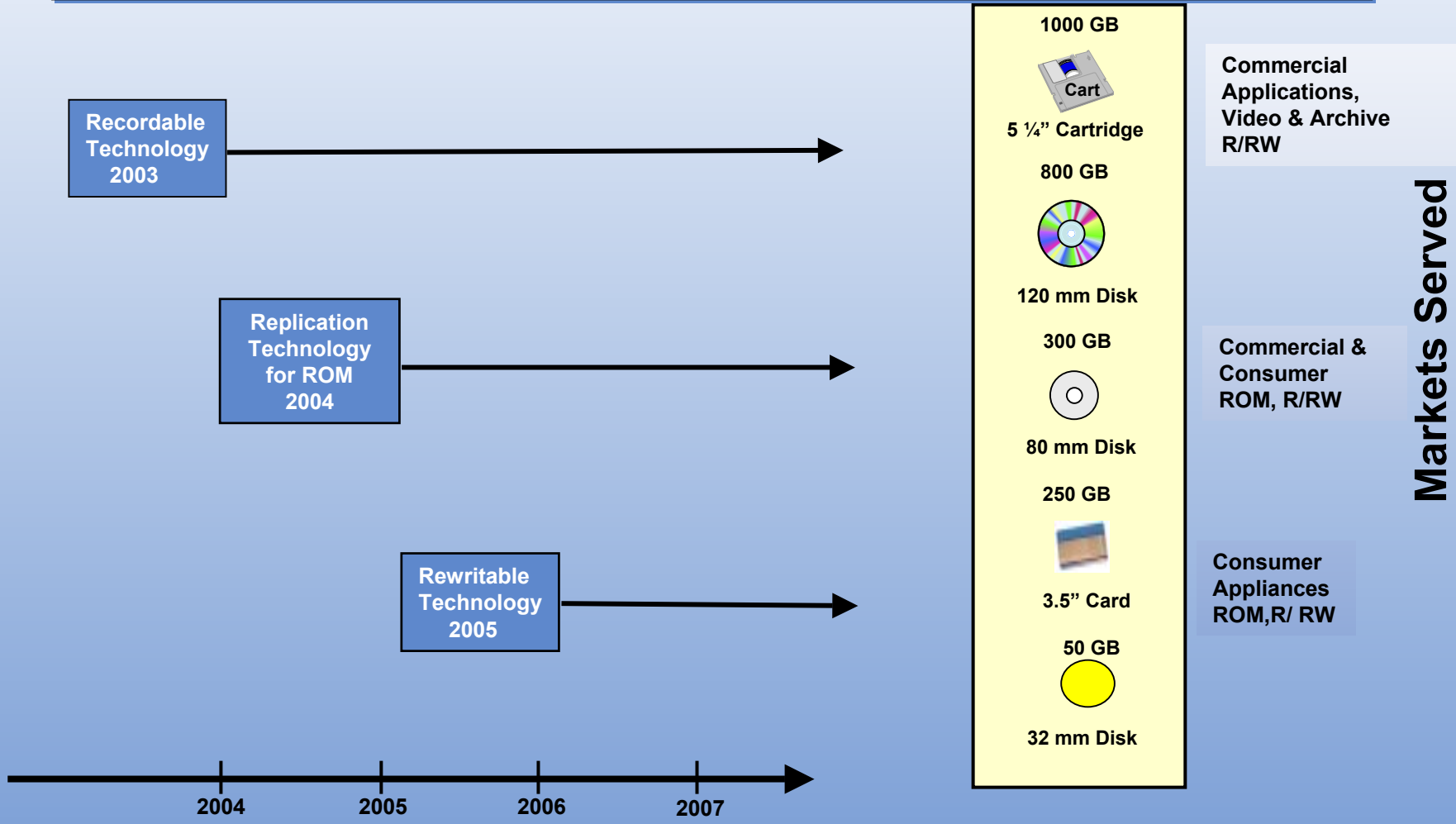
## **Mission**

**Bring holographic storage media and drives to market.**

## **History**

**Founded by Bell Labs media and holography scientists in December 2000.**

**Disruptive Vision:** Revolutionize the removable storage industry by becoming the underlying technology for all devices and media - **\$ 60B opportunity**



**Markets Served**

## What is holographic storage?

Holography stores data in an optical pattern of a million bits. The data are recorded and read with a single flash of light. Thousands of holograms can be stored in the same location in the media.

## What is its value?

Lowest Total Cost of Ownership of any high capacity, high performance removable storage, and the flexibility to address broad markets today, and tomorrow.

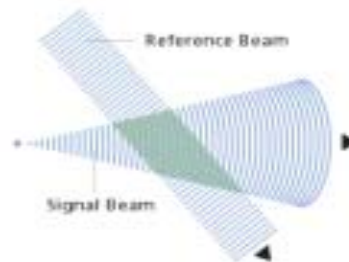
## Why InPhase?

It is the only company in the world with media and drive expertise, intellectual property, and resources to successfully commercialize the technology. (~80 patents and filings, and a staff of >50)

# What is a Hologram?

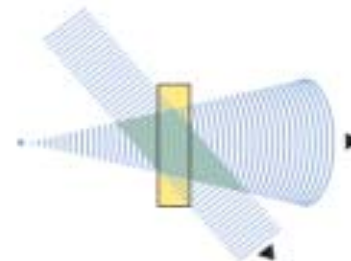
## 1 Recording

The intersection of two beams creates an interference pattern of bright and dark regions.



## 2 Recording

A photosensitive medium records the interference pattern.



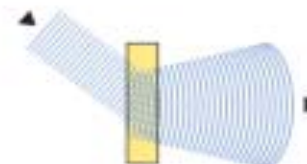
## 3 Recording

The hologram is the image of the interference pattern stored within the medium.



## 4 Reading

Light from one beam shining on the hologram reconstructs the data pattern.



# Why Holographic Storage?

- **High Capacity & Performance**
  - Highest optical density - 100 Gbits per sq. in. for initial product
  - 4X faster than Transfer rates of other optical technologies
  - Random Access
- **Robust Content Protection**
  - More difficult to pirate due to volume recording
- **Long Archival Life**
  - 50 years
  - Very tolerant to dust, scratches, and surface defects
  - Not effected by electric or magnetic fields
- **Low Cost**
  - Lowest cost per gigabyte for removable storage
  - Inexpensive media manufacturing process
- **Broad Design Flexibility**
  - Card or Disk formats – enabled by parallel read/write
  - Optical Mastering possible (ROM), recordable, rewritable

# Tapestry - a new paradigm in storage

	Existing storage	Tapestry
Capacity	Bit Size Bit Density	Media thickness Multiplexing technology Page characteristics
Transfer Rate	RPMs Linear bit density	Page record/recovery Media sensitivity Media dynamic range Laser power
Reliability	NFR increases susceptibility to dust, scratches, head crashes, E&M	Holographic not susceptible



# InPhase Breakthroughs

Required Components	Past Problems	InPhase Breakthroughs
Recording material	Commercially viable materials that had high density and were manufacturable did not exist	<b>2 Chemistry Media</b> <ul style="list-style-type: none"> <li>• For manufacturing properties</li> <li>• For recording properties</li> </ul>
High Volume Manufacturing	Optically flat media expensive to manufacture.	<b>ZeroWave™ mfg process</b> Low cost DVD like process
Recording Methods	Complex with limited densities.	<b>Patented</b> recording methods that enable high density
Channels and error correction codes	Serial storage channels.	Developed modulation, coding, and filtering for robustness and capacity.
Environmental stability	Changes to Media volume caused by temperature sensitivity.	<b>Methodology</b> that allows wide operating temperature ( ± 30°C)

# Tapestry 100

- **Media**

- Recordable
  - 5 ¼ inch media in a cartridge
  - Chip in cartridge for file system
  - Library ready
- ROM
  - Bare 120 mm disc
  - Does not require Cartridge
  - Uses same media formulation as Recordable



- **Drive**

- Recordable
  - 5 ¼ inch full height, extended depth.
  - 100 GB, 20 MB/sec
  - Library ready



# Technology Overview

# Holographic Data Storage

## Feature

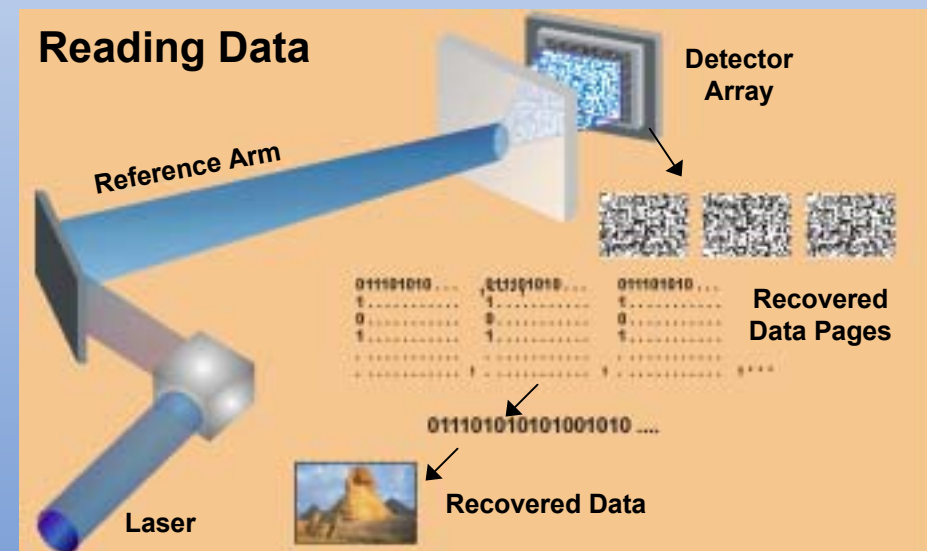
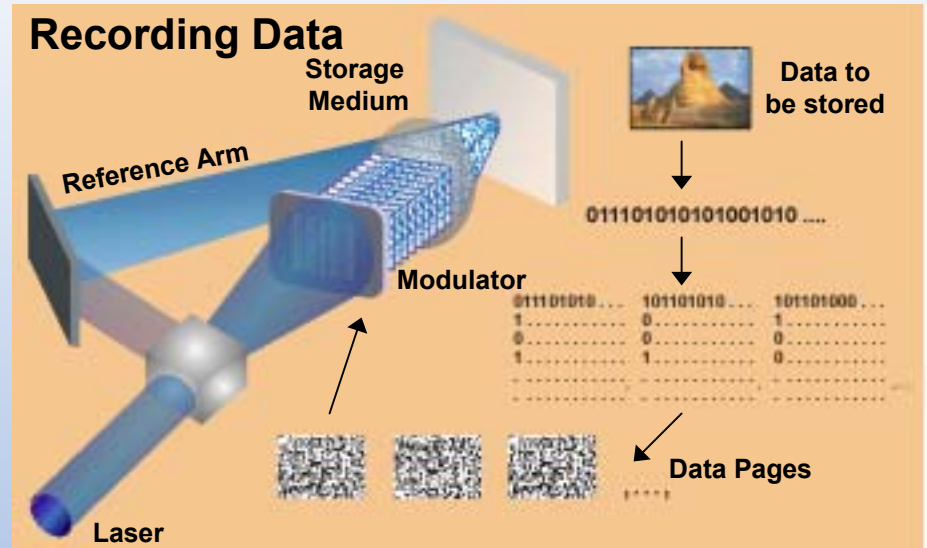
- Parallel access (million vs. one bit data transfers)
- Volumetric Storage (Overlap many data pages in one location)
- Removable Media

## Benefit

- Fast data transfer rates
- Ultrahigh storage densities
- Transportability

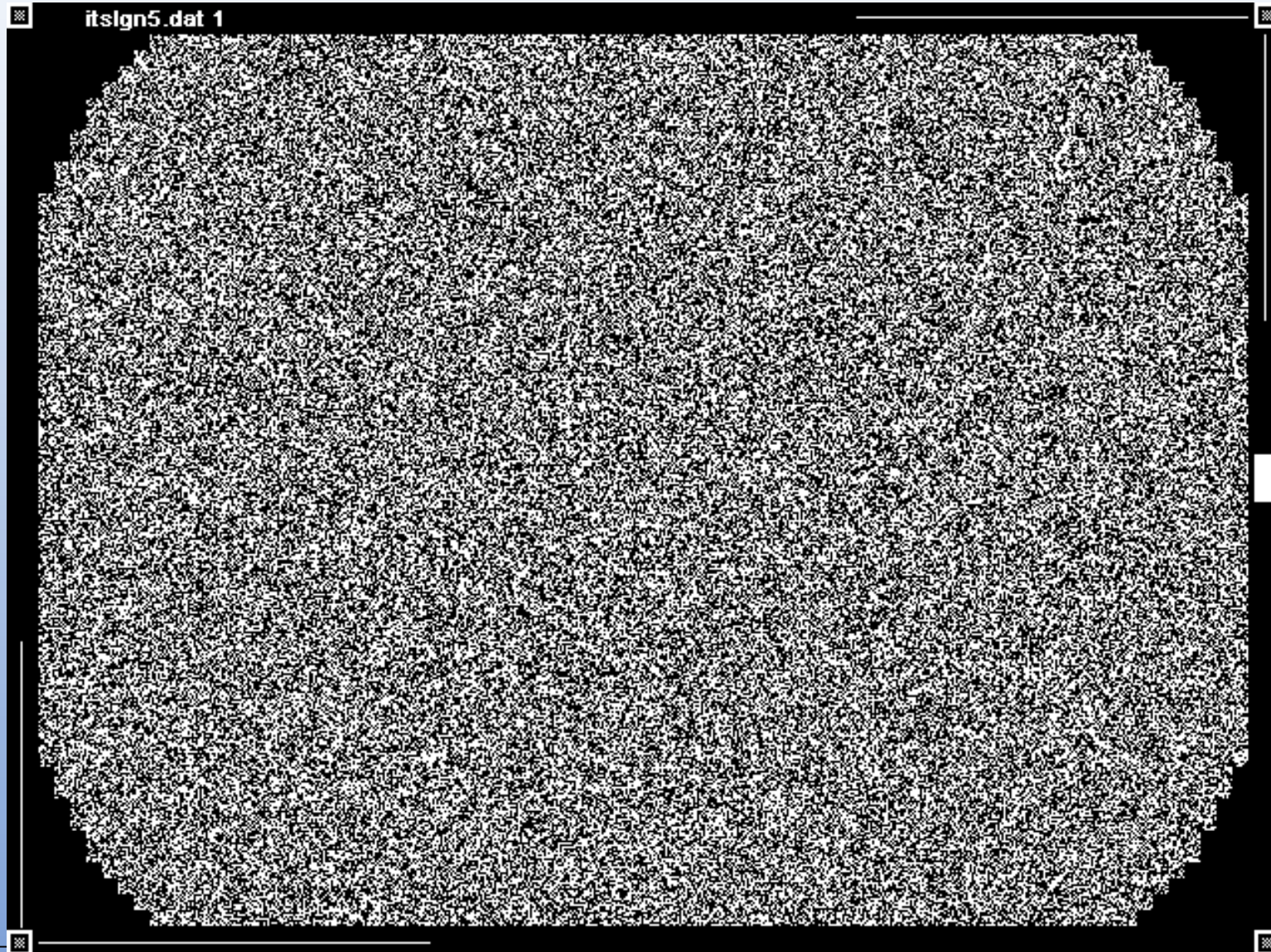
Record by crossing signal beam with a reference beam

Readout by presenting reference beam to the media



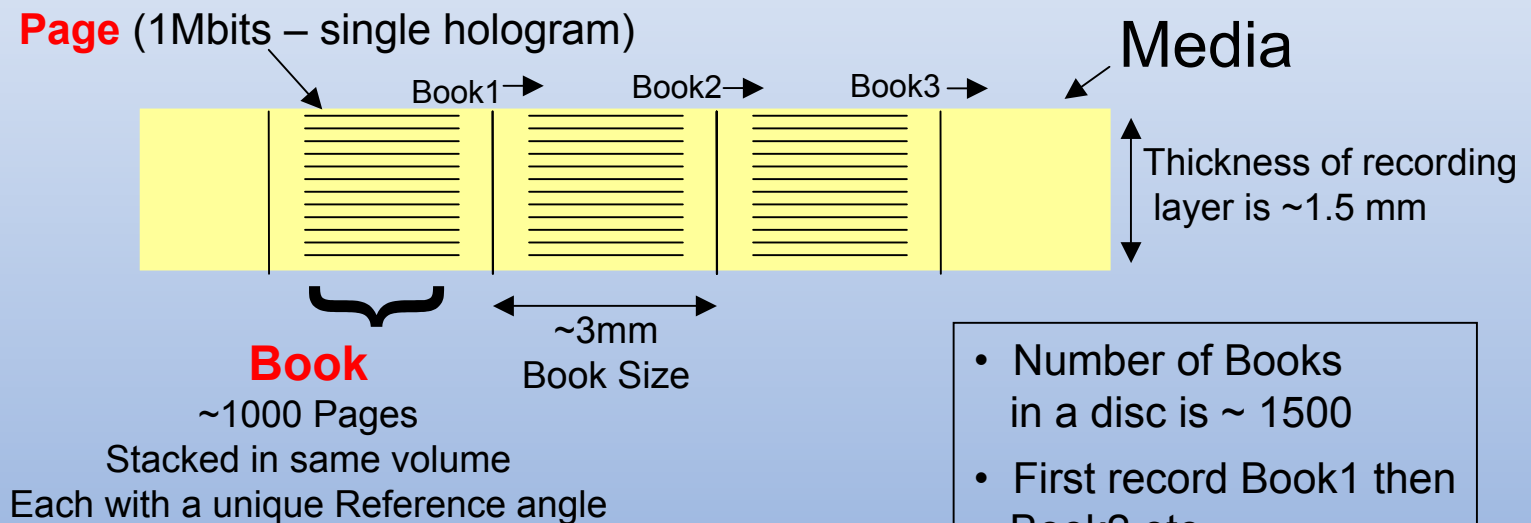


# Sample Data Page (1 million bits)



# Recording through the Volume

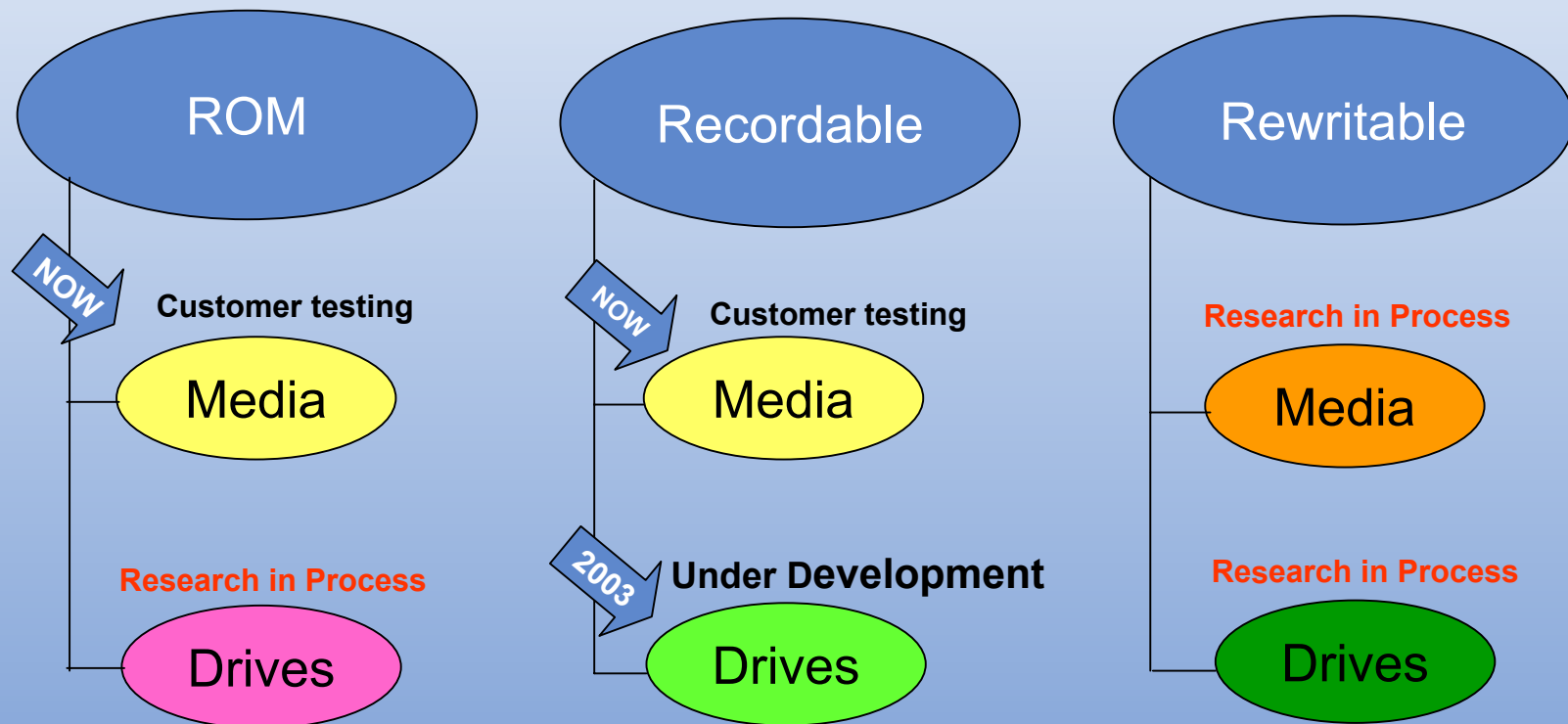
## Logical View



## Physical View

- Physically each page (hologram) takes the whole volume of the book
- The thickness of the recording layer allows each page to be readout and stored uniquely by changing the reference beam angle for each page.

# Technology Development Focus



# Media Overview



## Requirements for Media for Holographic Data Storage

**Dynamic Range** - High storage densities & rapid read rates

**Photosensitivity** - Rapid write rates

**Millimeter Thickness** - High storage densities

**Dimensional Stability** - High fidelity data recovery

**Optical Flatness** - High fidelity imaging of data pages

**Low Scatter** - Low levels of noise in data recovery

**Processing** - Heat/Solvent Free

**Non-volatile readout**

**Long shelf-life of media**

**Long archival life of stored data**

**Environmental/thermal stability**

**Manufacturing Cycle Time**

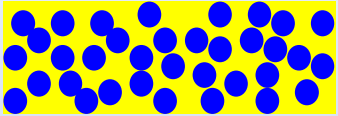
**Manufacturing Cost**

**Mastering Marks on Media**

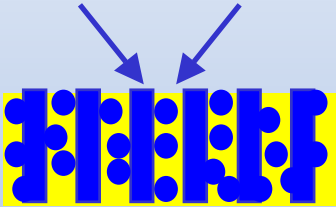
## Selected candidate Materials for Recording

	Dynamic Range	Photo Sensitivity	Dimensional Stability	Thickness	Optical Quality	Non-volatile/ Post-Processing	Media Cost
<b>InPhase Tapestry Media</b>	✓	✓	✓	✓	✓	✓	✓
Photorefractive crystals (eg LiNbO3)	X	X	✓	✓	✓	X	X
Photorefractive polymers	X	X	X	X	-	X	X
Inorganic Glasses	X	X	✓	✓	-	-	X
Biological /Photochromic	X	X	-	-	-	X	X
Conventional Photopolymers	-	✓	X	X	X	✓	-

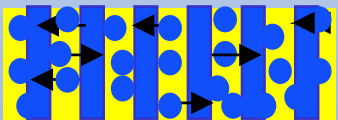
## Mechanism



System consists of monomers dissolved in a matrix.



Holographic exposure produces a spatial pattern of photoinitiated polymerization.



Concentration gradient in unreacted monomers induces diffusion of species.



Diffusion produces a compositional gradient, establishing a refractive index grating ( $\Delta n$ ).

## Advantages

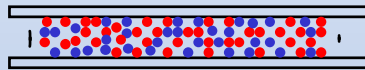
- High photosensitivity
- Permanent holograms
- Low cost

## Concerns

- Recording-induced dimensional & bulk refractive index changes
- Thickness
- Optical Quality & Scatter

# InPhase's Tapestry™ Recording Material

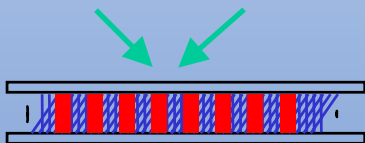
## Proprietary Two Chemistry Approach



*Resin consists of matrix precursors  
and imaging components*



*In-situ formation of cross-linked matrix*



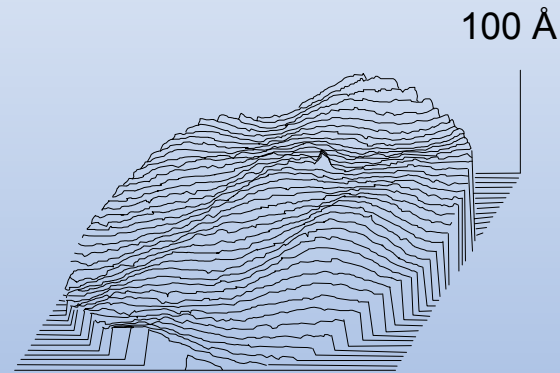
*Writing chemistry is independent of  
host formation chemistry*

Media is fabricated from independently polymerizable and compatible matrix and imaging components

- ✓ **In-situ matrix formation:** thick, optically flat formats with good mechanical robustness
- ✓ **Cross-linked matrix:** stable holographic gratings - long archival life
- ✓ **Compatible matrix and monomer systems:** optical clarity and low levels of light scatter
- ✓ **Independent matrix and monomer systems:** no cross-reactions- maximizes refractive index contrast.

# InPhase Zerowave™ Media Manufacturing Process

**Excellent optical quality & thick media**



**3" x 3", 1 mm-thick media**

**Proprietary DVD-like media fabrication method  
allows for**

Routine fabrication of media with better than  $\lambda/4$  / cm<sup>2</sup>  
flatness enables high fidelity data storage and recovery

# Optical Quality: Pixel Matching with Low Bit Error Rates



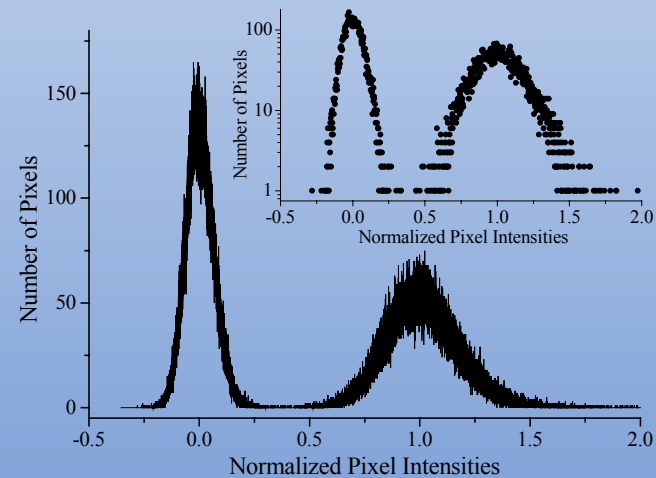
Expanded view of corner pixels

Histogram of pixel intensities, a measure of fidelity of data recovery.

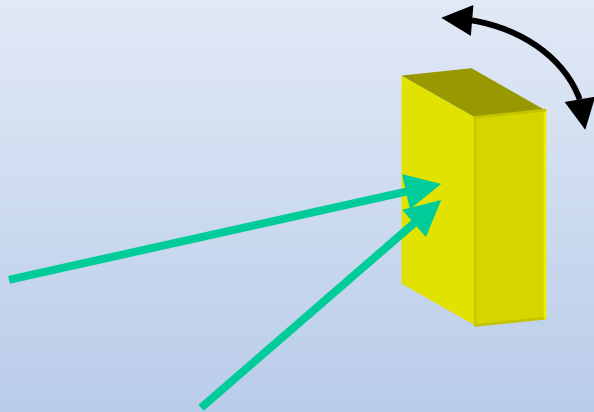
Raw BER  $\sim 10^{-6}$



Data Page 800x600



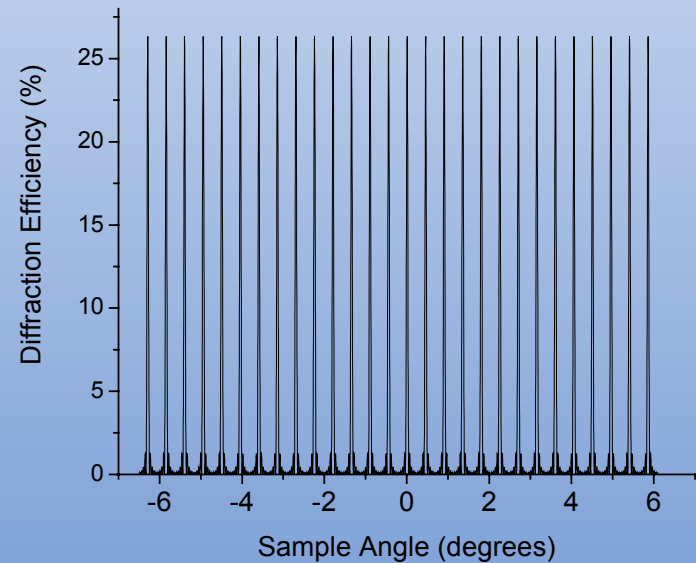
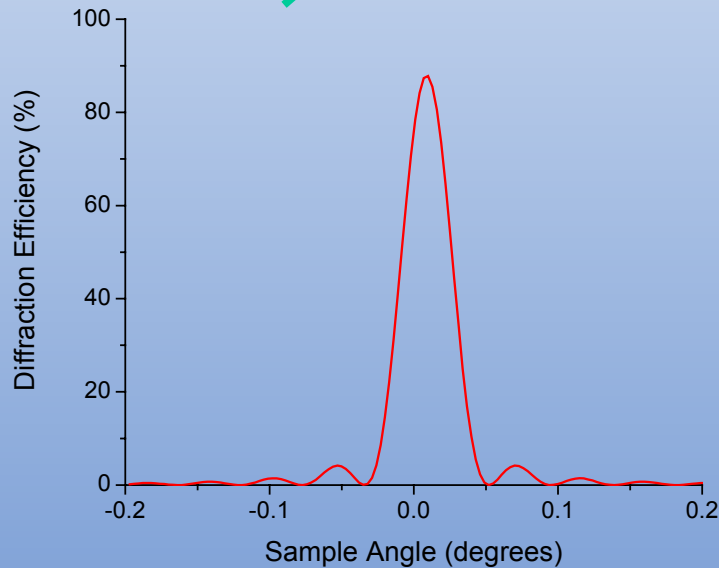
# Measurements of Dynamic Range



**Measure of Dynamic Range:  $M/\#$**

$$M/\# = (\text{Number of Holograms}) * (\text{Ave. Diff. Eff.})^{1/2}$$

$$M/\# \sim \Delta n * (\text{thickness})$$

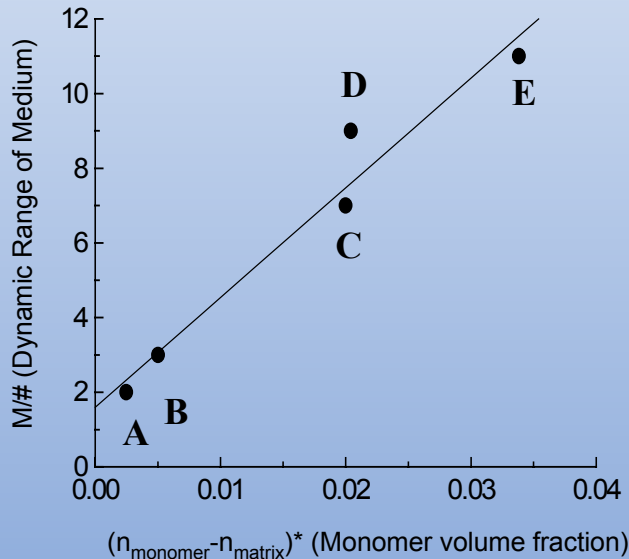


# High Dynamic Range Photopolymer Media

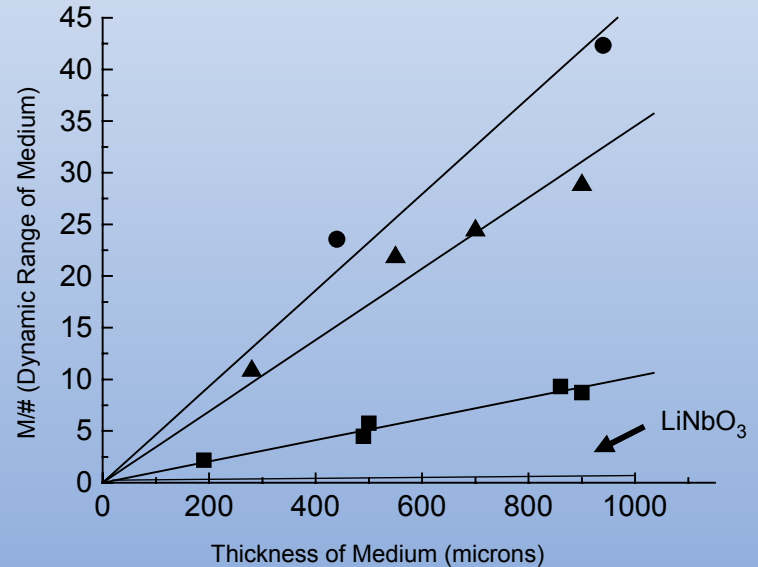
Independent Matrix & Writing Chemistries Yield High Dynamic Range Media:  
Tunable Dynamic Range with Controlled Dimensional Change

Dynamic range can be systematically optimized by using writing monomers of increasing refractive index and size.

Concentration of writing monomers is adjusted to achieve equal levels of Bragg detuning (dimensional stability) throughout the series.



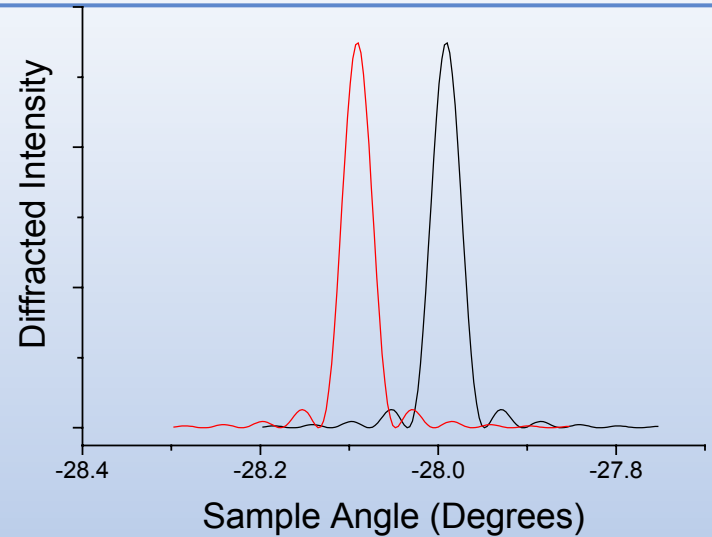
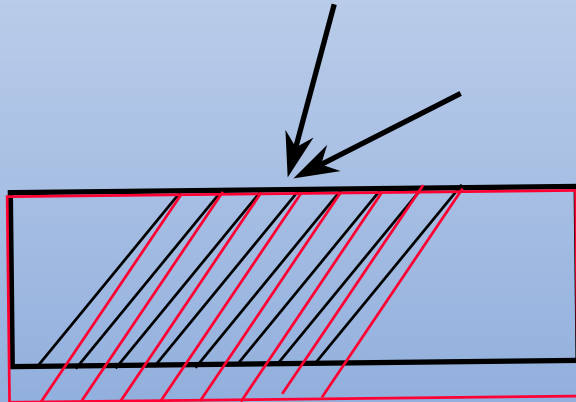
M/# of a series of 200 μm thick media fabricated with writing monomers A-E



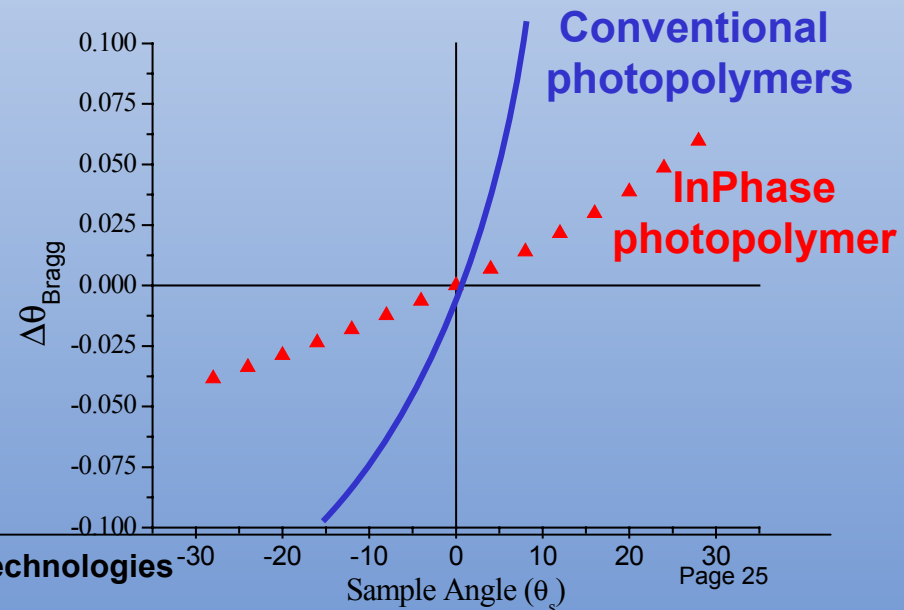


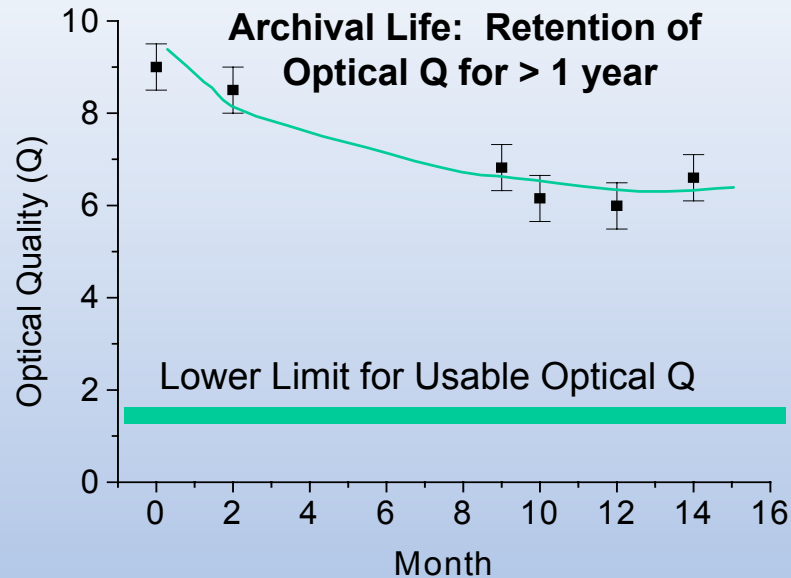
## Dimensional Stability

Changes in dimension (shrinkage) distort holographic gratings leading to **detuning** of the gratings' Bragg angles

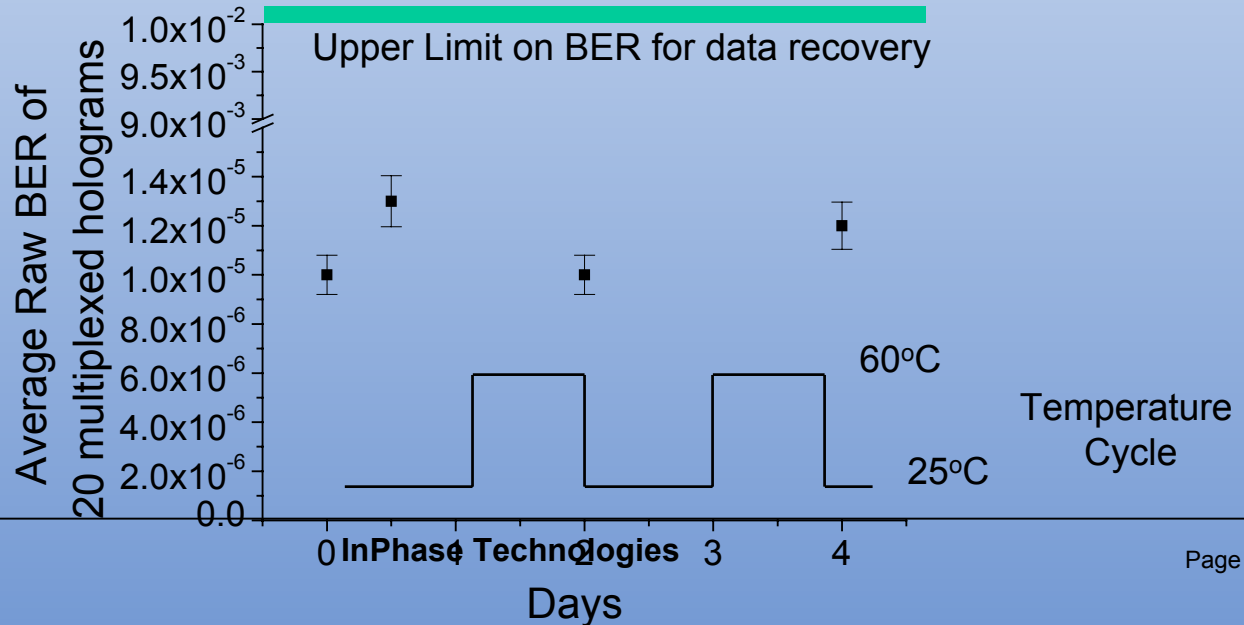


## Recording-Induced Bragg Detuning



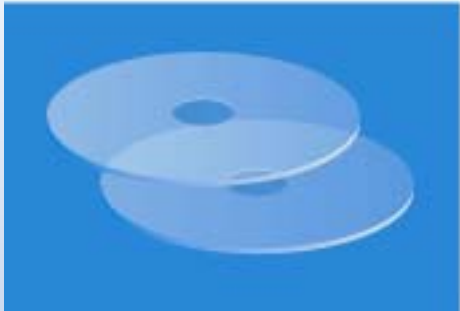


**Archival Life:  
Accelerated aging tests  
of retention fidelity of  
data recovery**

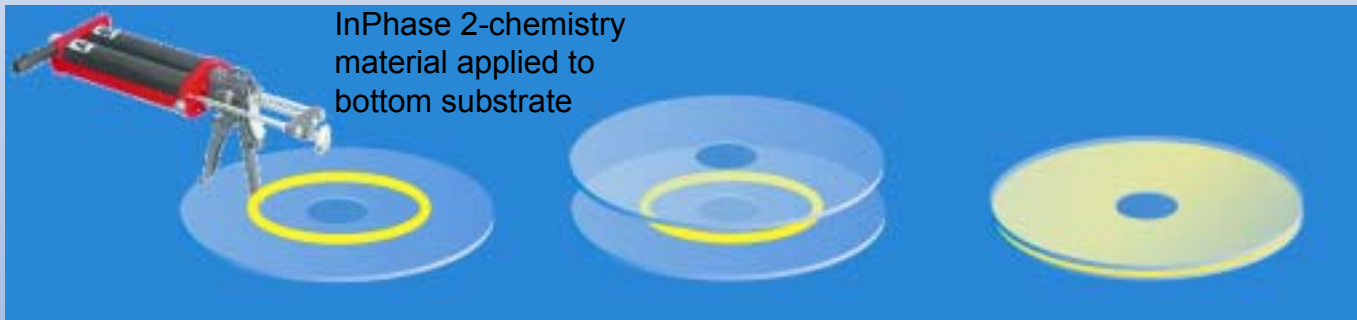


## Present Status Photopolymer Media

	<u>Goal</u>	<u>Current Media</u>
Dynamic Range (M/# at 1mm)	10-15	>20
Photosensitivity ( $\Delta n / (mJ/cm^2)$ )	$>1.2 \times 10^{-6}$	$9 \times 10^{-6}$
Millimeter Thickness	$\geq 1$ mm	>1 mm
Shrinkage	$\leq 0.1\%$	$\leq 0.1\%$
Optical Flatness	$\leq \lambda/2$ /cm	$< \lambda/4$ /cm
Low Scatter (of ref. power)	$\leq 10^{-6}$	$< 10^{-6}$
Works in Red, Green, and Blue $\lambda$ s	✓	✓
Heat/Solvent-Free Processing	✓	✓
Non-volatile readout	✓	✓
Shelf-life of media	>3 year	tested >6 months
Archival life of stored data	>30 years	tests underway

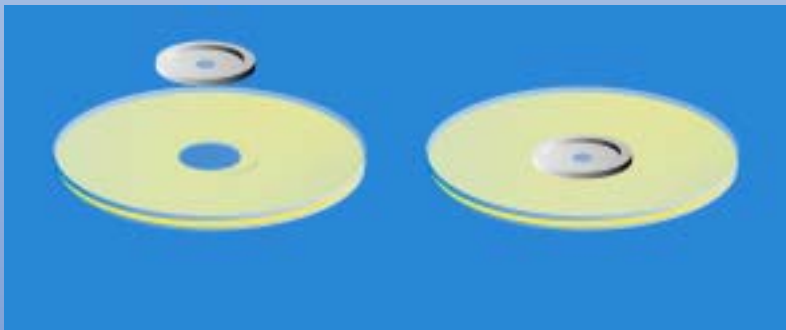


Plastic substrates fabricated via DVD molding process



InPhase 2-chemistry material applied to bottom substrate

Substrate-polymer-substrate sandwich formed via DVD-like bonding process



Hub attached

# Media Summary Status

- **Currently selling media to customers building holographic drives**
  - **ROM products**
  - **Recordable products**
- **Contract with automation company to develop media manufacturing system for volume production**
- **Rewriteable media under development**

# Drive Overview

# Recordable/Rewritable Technology Roadmap

	2003	2004	2005	2006	2007
<b>Recordable Specs</b>	100 Gb/in <sup>2</sup> 20 MB/s	200 Gb/in <sup>2</sup> 40 MB/s	400 Gb/in <sup>2</sup> 80 MB/s	800 Gb/in <sup>2</sup> 160 MB/s	1600 Gb/in <sup>2</sup> 250 MB/s
<b>Drive Configuration</b>	<ul style="list-style-type: none"> <li>• Angle Mux ~1000 pages</li> <li>• Blue Laser</li> </ul>	<ul style="list-style-type: none"> <li>• Custom SLM, Detector</li> <li>• Grayscale</li> </ul>	<ul style="list-style-type: none"> <li>• 2000 pages by using 2 wavelengths</li> </ul>	<ul style="list-style-type: none"> <li>• Custom laser</li> <li>• 4 <math>\lambda</math>'s</li> </ul>	<ul style="list-style-type: none"> <li>• 8 <math>\lambda</math>'s</li> <li>• Or more angles used</li> </ul>
<b>Re-Writable Specs</b>			200 Gb/in <sup>2</sup> 30 MB/s	400 Gb/in <sup>2</sup> 60 MB/s	800 Gb/in <sup>2</sup> 120 MB/s
<b>Drive Configuration</b>			<ul style="list-style-type: none"> <li>• Custom SLM, Detector</li> <li>• Grayscale</li> </ul>	<ul style="list-style-type: none"> <li>• 2000 pages by using 2 wavelengths</li> </ul>	<ul style="list-style-type: none"> <li>• Custom laser</li> <li>• 4 <math>\lambda</math>'s</li> </ul>

## Initial product target specifications

- Capacity (native): 100 GBytes
- Transfer rate (read and write) 20 MB/sec
- Average seek time: 250 msec
- Maximum seek time: 500 msec
- Interface (at FRS): SCSI-II
- Cartridge load time: 5.5 sec
- Cartridge unload time: 3.5 sec
  
- MTBF 100K POH's
- MTTR 30 min
- MSBF (Mean Swaps between failure) >750K cycles



# Test Beds for Media, Servo, and Channel



## Program risks and opportunities:

- No known “show-stoppers” at this time.
- Test Beds & Prototypes will identify and explain technology unknowns
- Blue Laser supplier not identified yet, but optical path is independent of the laser supplier
- Timely identification of the OMA and Drive MFG partners.

## InPhase Summary

- **Large markets are demanding advanced removable storage**
  - Holographic storage has compelling value proposition
- **InPhase has a commercial media**
  - Proprietary photopolymer system with two chemistry approach
  - Innovative, DVD like, manufacturing process
  - Applicability to markets outside of storage (such as photonics)
- **Strong IP portfolio and management team**
- **Technology roadmap for significant improvements**
  - This is a technology with legs
  - Re-writable roadmap opens even larger markets