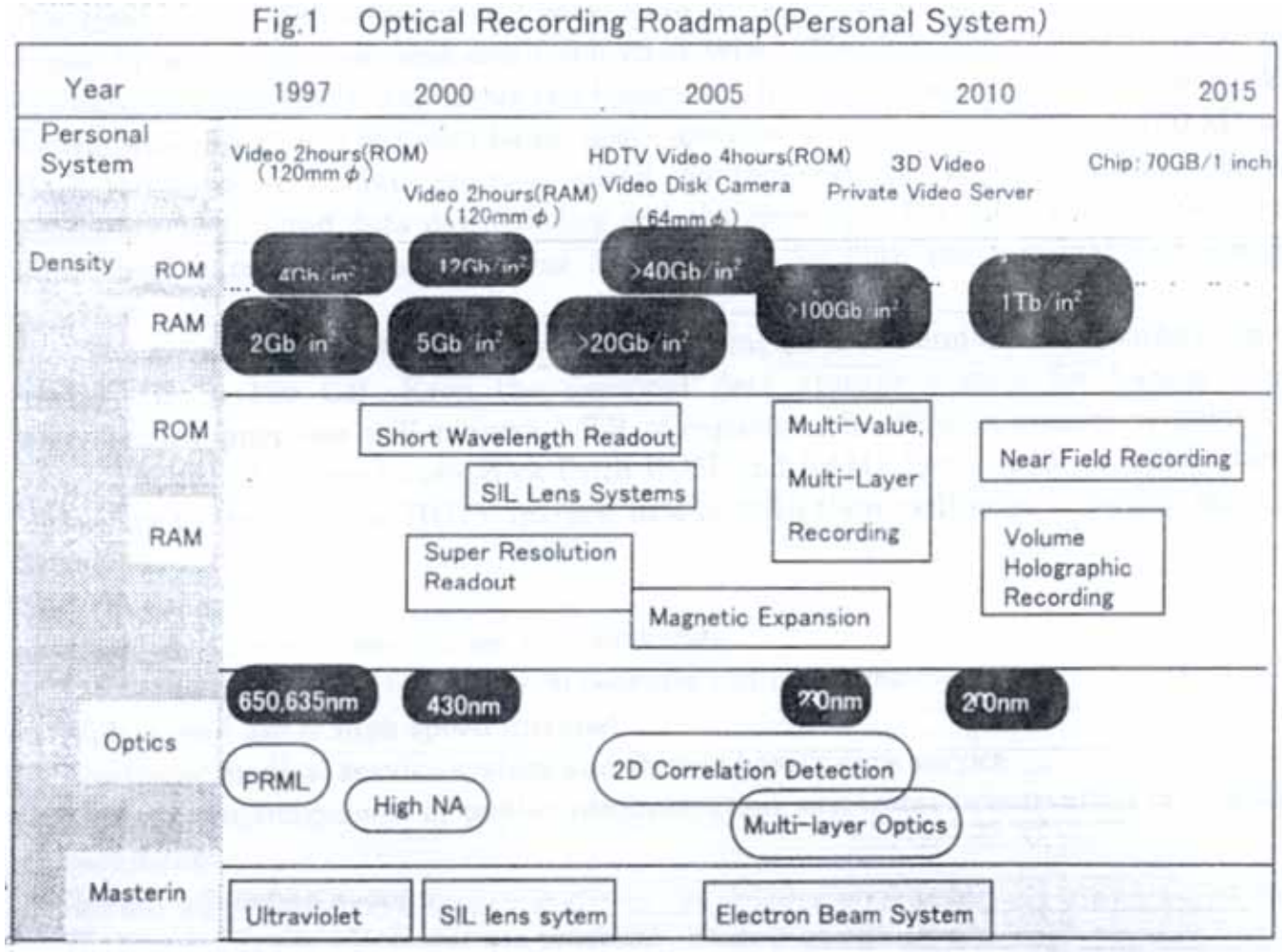
Holographic Data Storage and Other Optical Data Storage Technologies

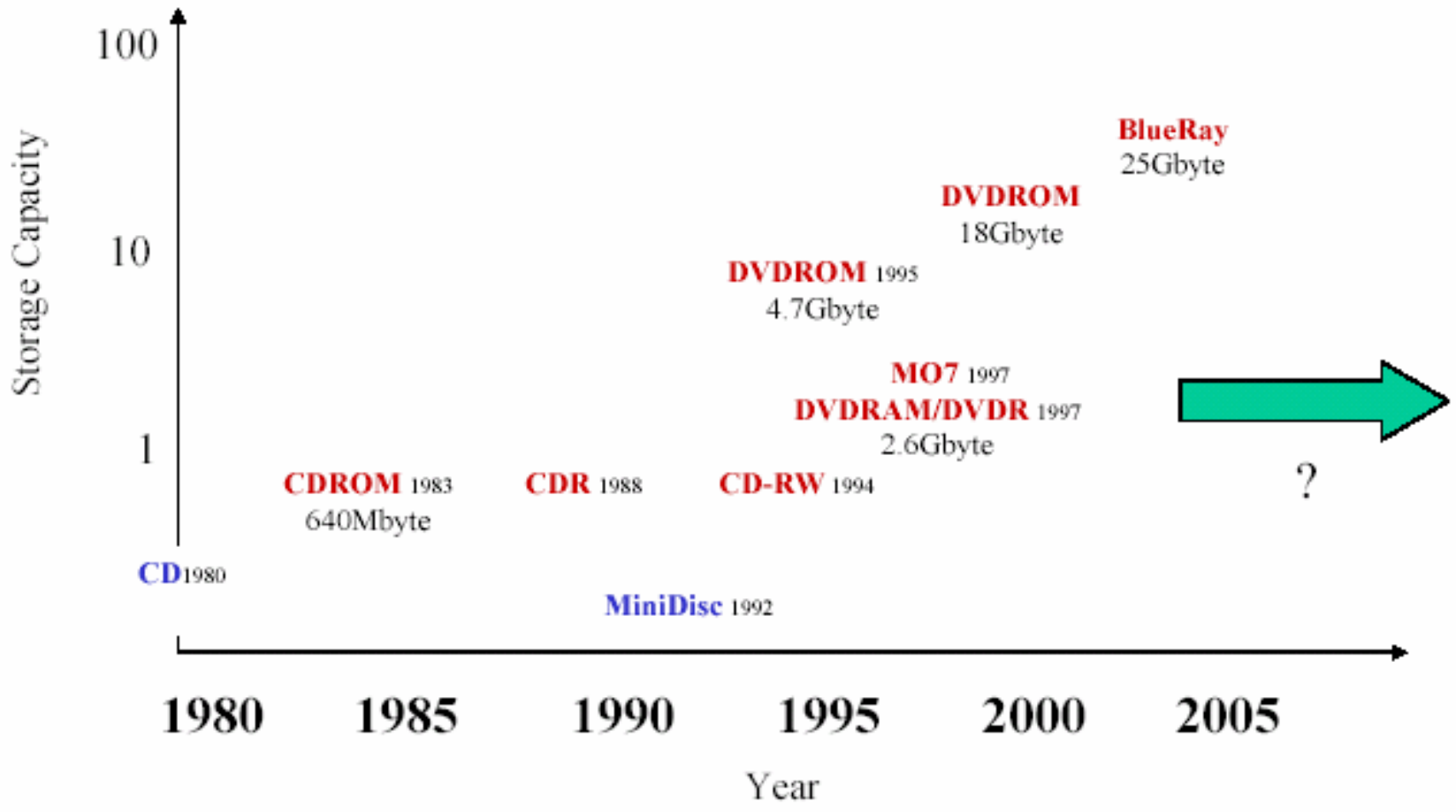
이병호
서울대학교 전기공학부
byoungho@snu.ac.kr
2007. 11. 8.

Optical Data Storage

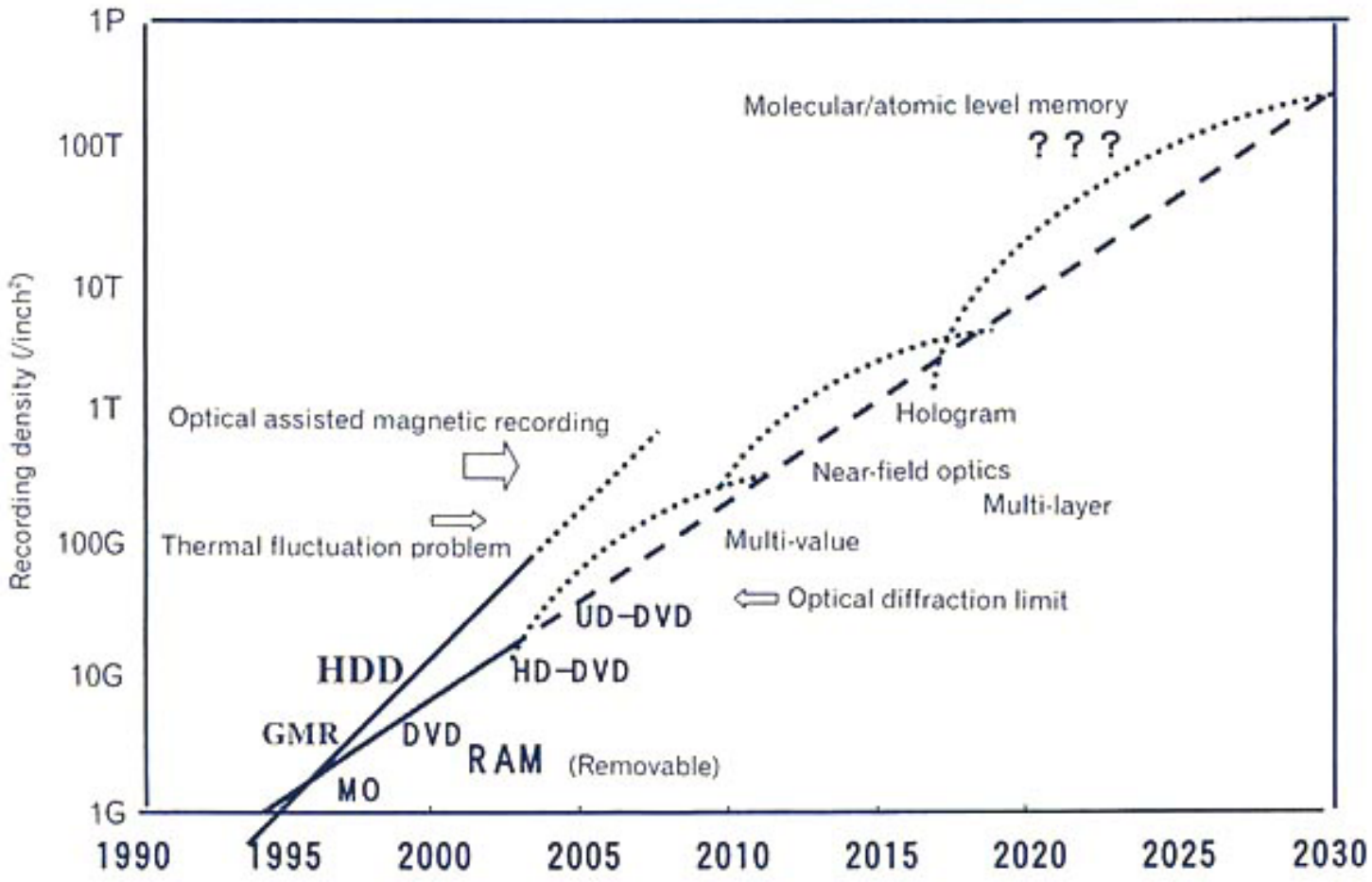
Roadmap of ODS



Optical Storage Roadmap

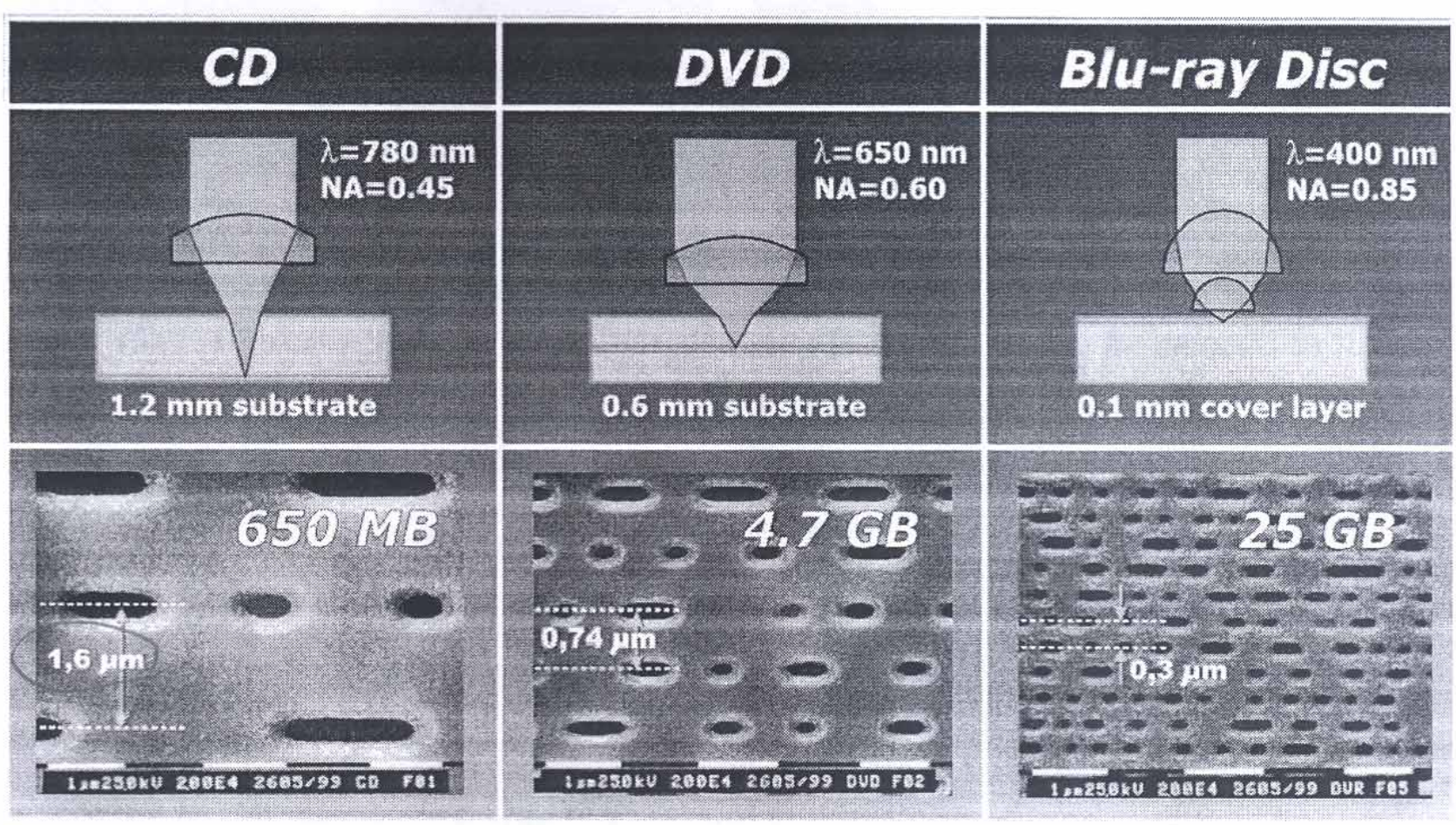


Memory Technology Roadmap



[OITDA Newsletter Mar 20,2002 No.16]

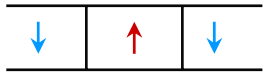
History of Optical Memory Technology



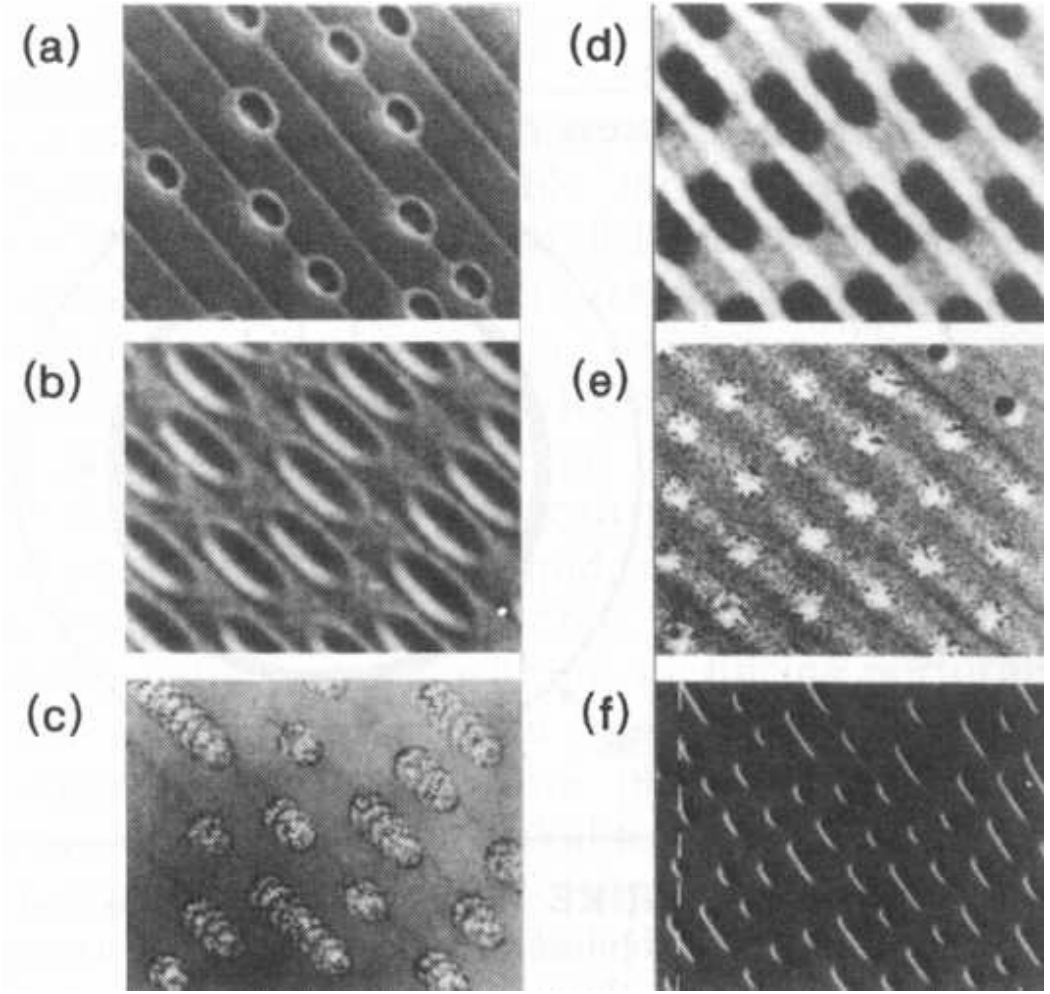
* 2005 Topical Meeting on Nano-Optical Probe

Optical Storage

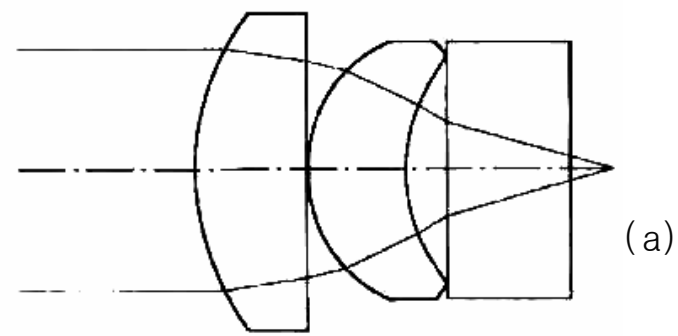
CD-R(WORM) and CD-E

Type		Principle		Feature
		Write	Read	
Read-Only		Phase Pit 	Diffraction	Mass Productive
Write-Once		Burned Hole 	Reflectivity Change	Long Archi-val Life
Re-writable	Magneto-Optic	Magnetization Direction 	Polarization Rotation	Erasable
	Phase-change	Crystal/Amorphous 	Reflectivity Change	

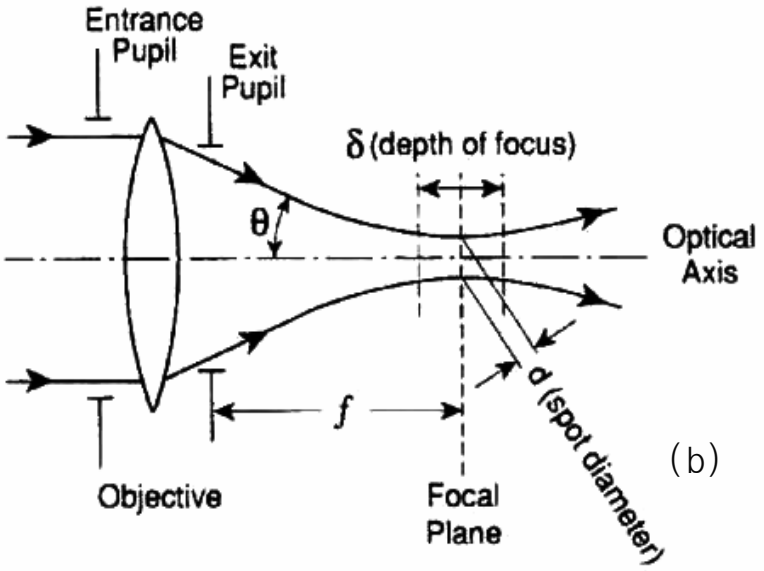
Optical Disk Data Storage (I)



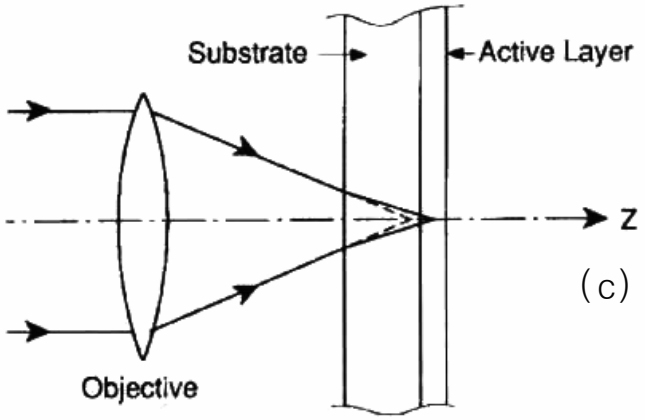
Optical Disk Data Storage (II)



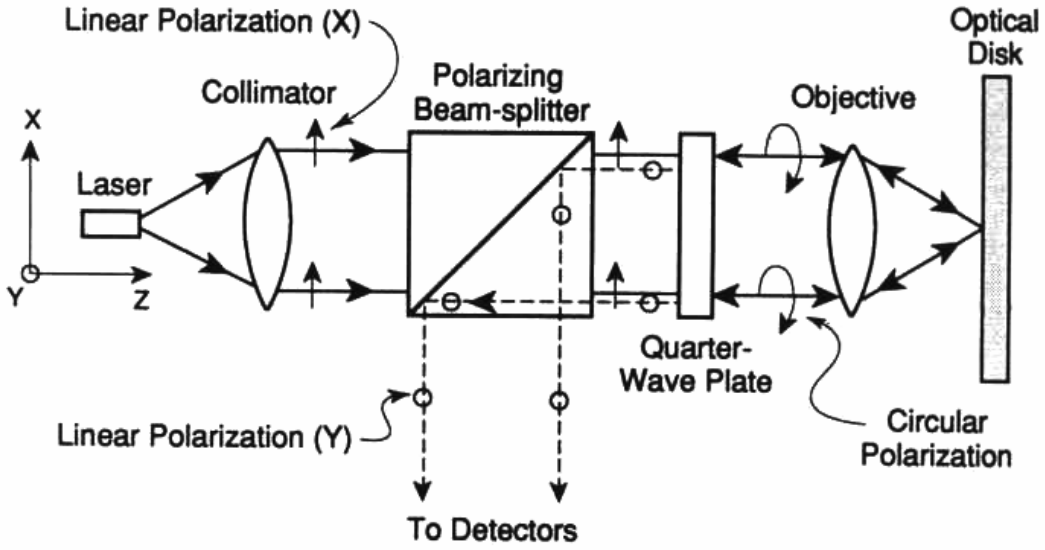
(a)



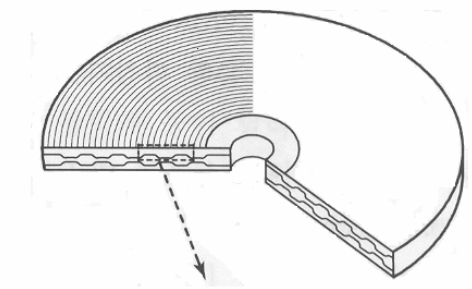
(b)

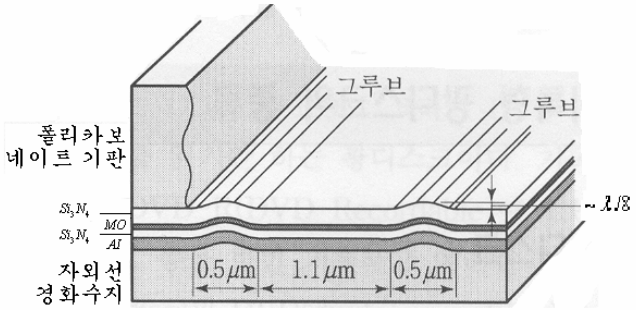


(c)



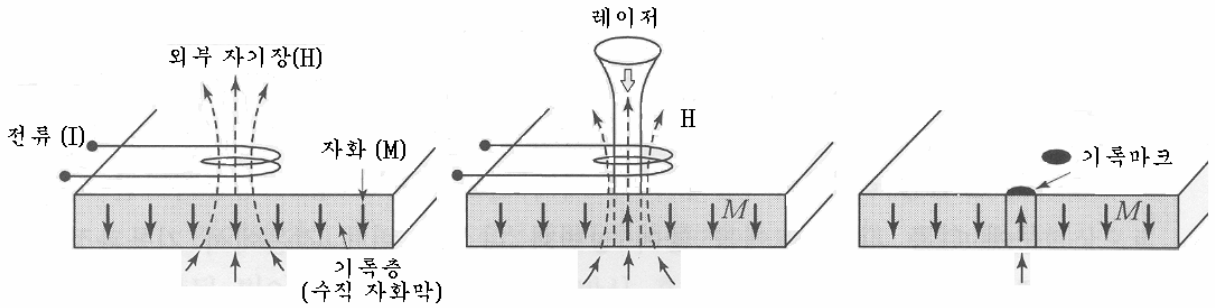
Magneto-optical Disc





광자기디스크의 구조

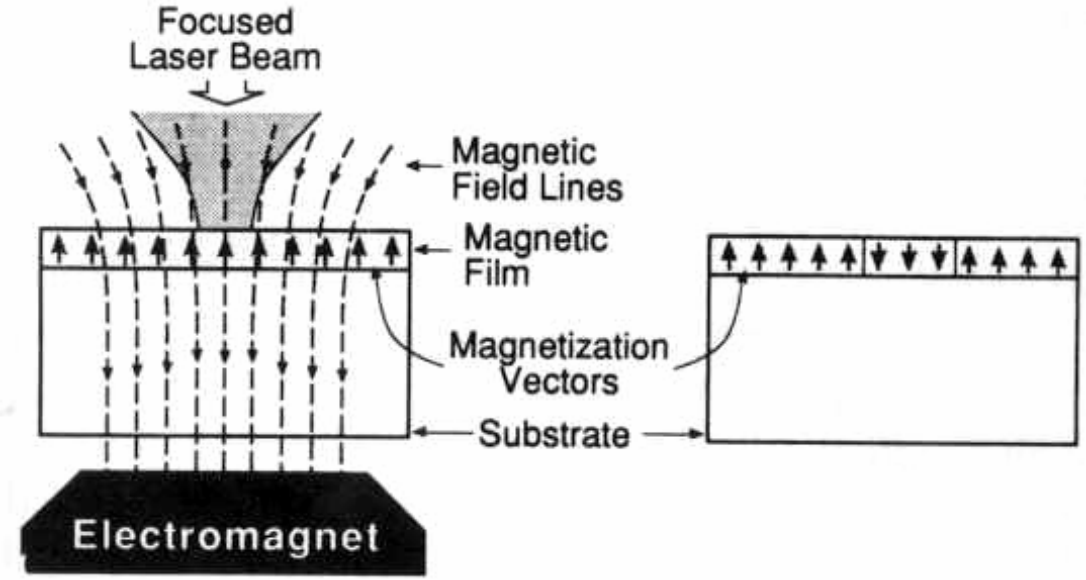
* 김 수 경, 최신 광 정보저장기술 2002



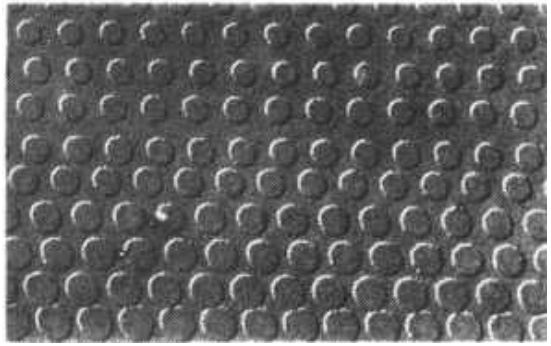
광자기디스크의 기록과정

- 광자기디스크의 기록과정
  - 기록하고자 하는 영역에 집속된 레이저광 조사 → **Curie**온도 → 자화**&**보자력감소 → 외부자기장 인가 → 외부 자기장 방향으로 자화 → 기록마크 형성
- 광자기디스크 기록밀도 $D = 0.61\frac{\lambda}{NA}$

Thermomagnetic Recording



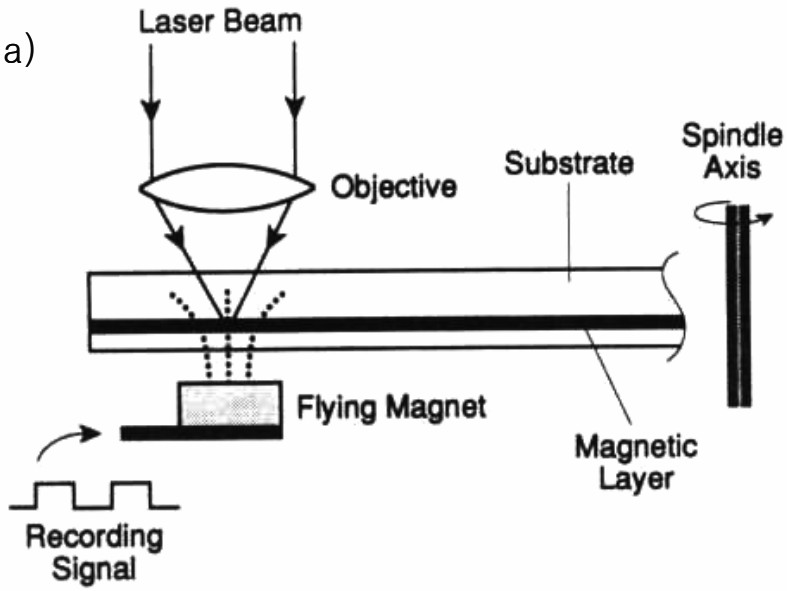
(a)



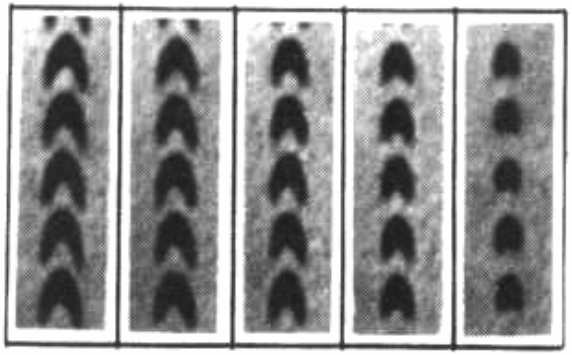
(b)

Recording by Magnetic Field Modulation

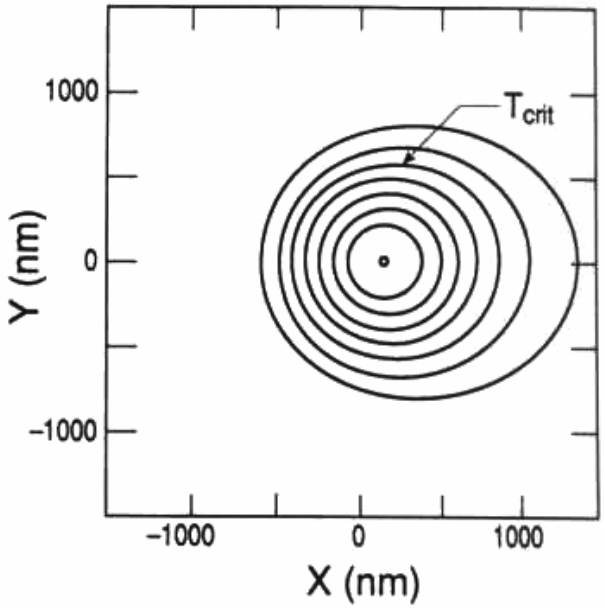
(a)



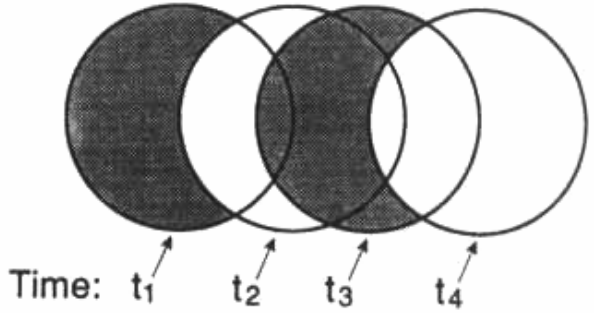
(b)



(c)

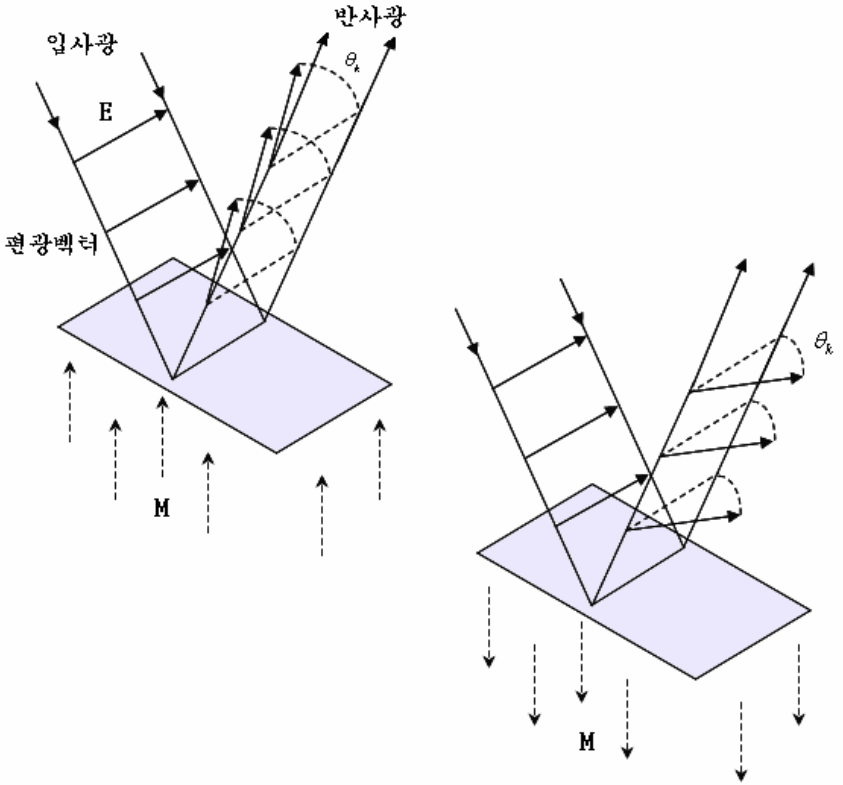


(d)



광자기디스크의 재생원리

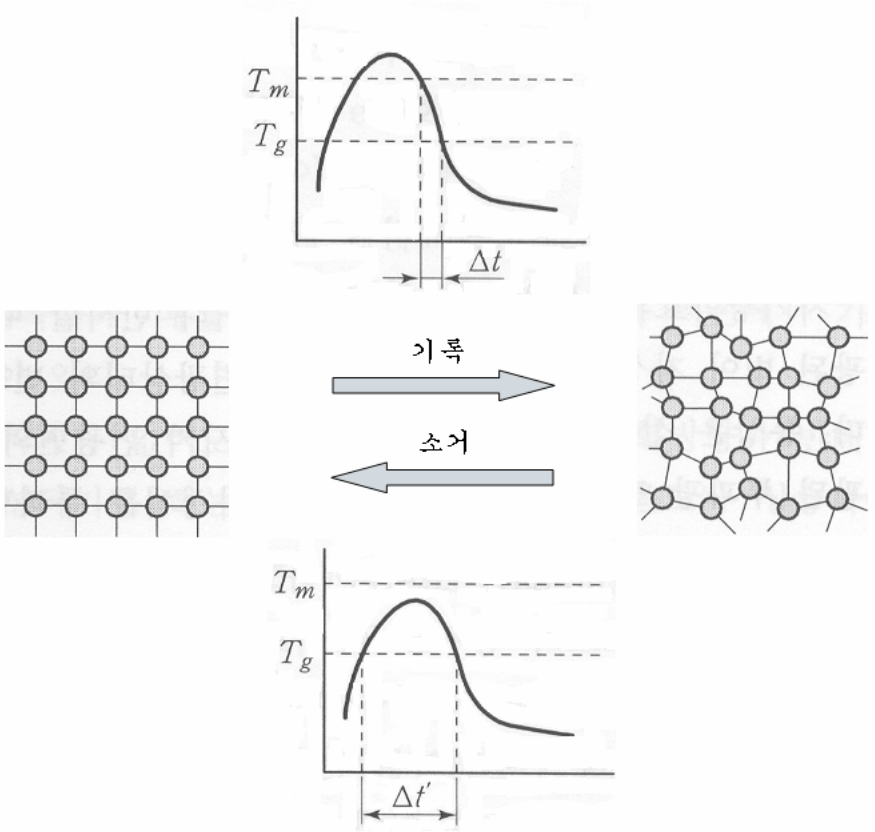
- 자기광학효과
  - 빛이 자성체를 투과하거나 반사할 때 생겨나는 현상으로, 편광된 빛이 자성체를 투과 또는 반사 후 편광상태의 변화가 일어난다.
- 기록된 마크의 자화 방향이 입사광의 진행방향과 같은 방향인가 반대방향인가에 따라 편광면의 회전방향이 달라지는 현상을 이용하여 디지털신호를 검출.



Kerr 효과의 개략도(편광벡터의 회전방향은 자화(M)방향에 따라 달라짐 $(0.2 \sim 0.3^{o})$)

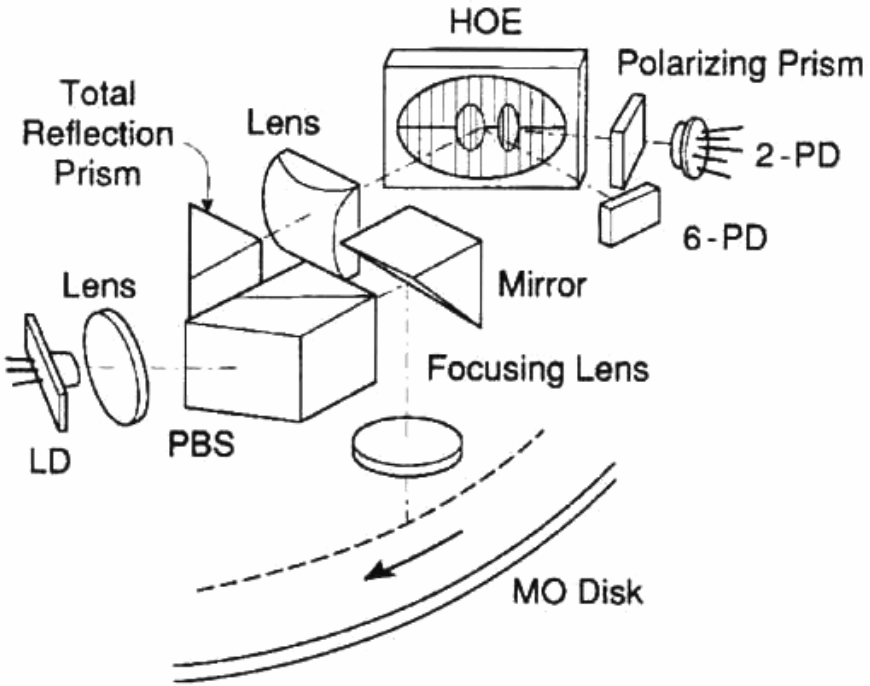
Phase Change Disc

- 상 변화 디스크는 규칙정인 원자배열을 갖는 결정질상 **(Crystalline phase)**과 불규칙적인 원자배열을 갖는 비정질상 **(amorphous phase)**간의 상변화 특성을 광 기록에 이용하는 기록방법이다.

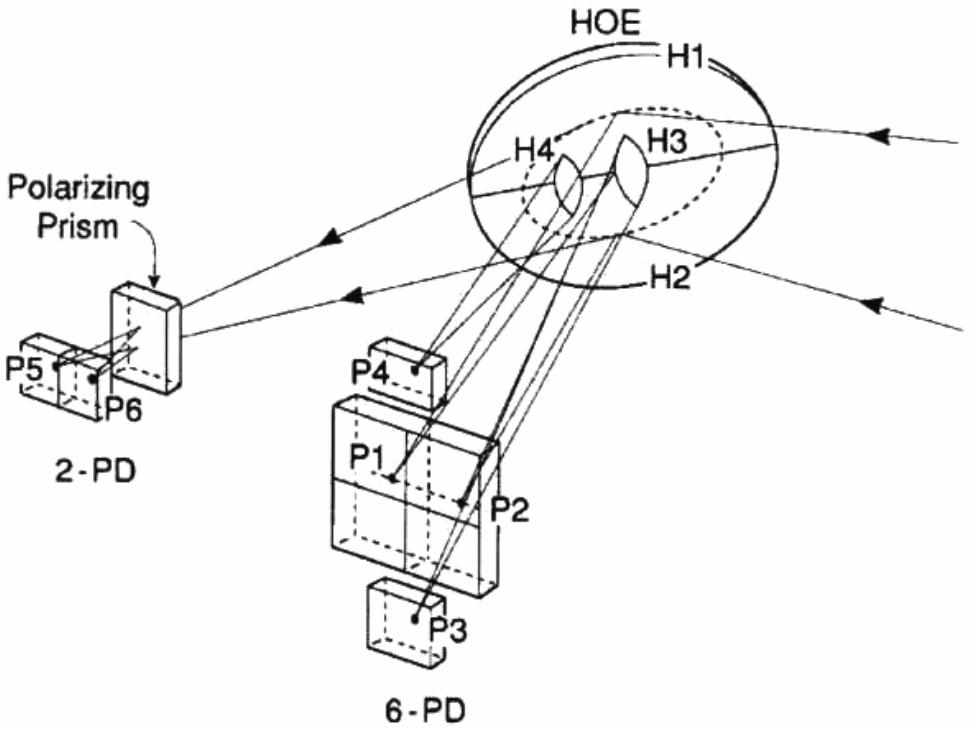


결정질과 비정질상의 원자배열 및
기록/소거과정의 기록층의 온도변화

Use of Diffractive Optics



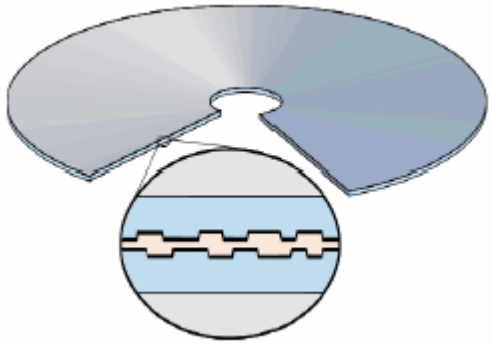
(a)



(b)

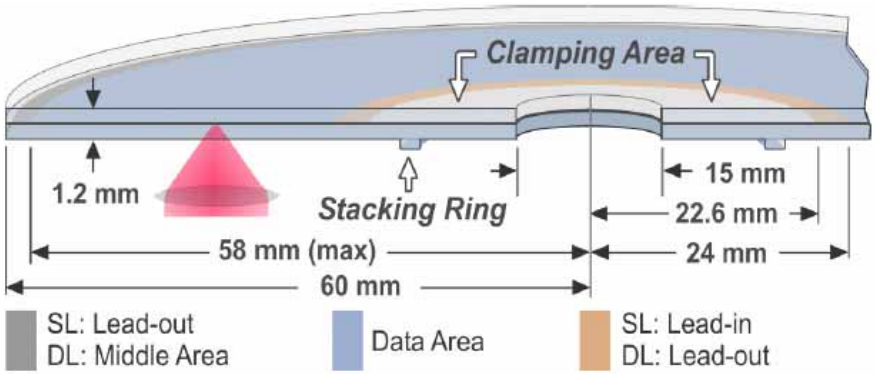
DVD (digital versatile disc) 구조

- 외형은 **CD**와 동일
- 직경 **120mm,** 두께 **1.2mm**의 얇은 알루미늄
- 원판에 플라스틱 막이 보호 막으로 덮여 있음



DVD Construction

- 내부구조
- 옆면을 자세히 보면 **2**장의 디스크가 겹쳐있음
- ‘용량 늘리기’를 위해 **0.6mm** 원판 **2**장 사용

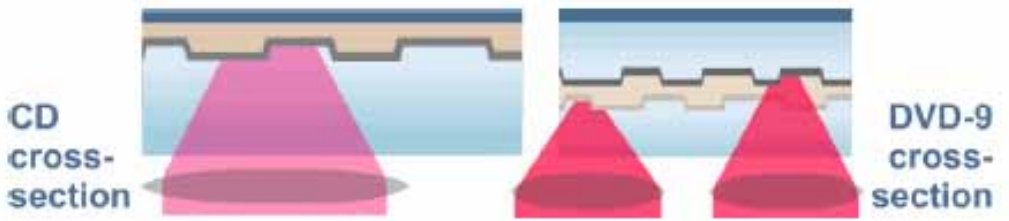


DVD Disc Layout and Dimension

* 출처 : Deluxe global media services ltd

DVD (digital versatile disc) 구조

- **DVD VS CD**
- 외관은 비슷하지만 내부가 다름
- **DVD**는 레이저 파장이 짧고 가늘다. **(->** 호환성 없음 **->** 렌즈를 **2**개 장착**)**
- **DVD**는 이중계층 구조이다. **(4.7GB, 8.5GB, 9.4GB, 17GB** 가능**)**
- **DVD**는 레이저 파장이 **2**개이다. **(**초점거리**)**
- 안정성
  - 겉면 코팅으로 **CD**와 같은 내부 데이터 보호가능



Cross-section of CD and DVD-9 discs

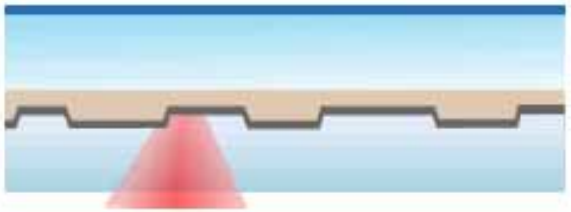
Parameter	CD	DVD	Comments
Sides	1	1 or 2	See 2.1
Layers	1	1 or 2	
Capacity (GB)	0.68	4.7 - 17	1 GB = 10^9 bytes (not 1024^3)
Track pitch (μ)	1.6	0.74	Radial distance between pits
Minimum pit length (μ)	0.83	0.4	For I3 pit
Wavelength (nm)	780	650	of laser diode pickup
Numerical aperture (NA)	0.45	0.6	defines angle of beam
Linear velocity (m/s)	1.3	3.49	at nominal 1x speed

DVD Disc Parameters

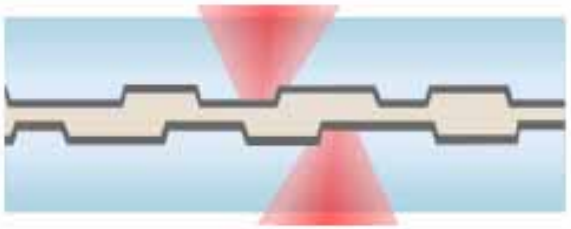
* 출처 : Deluxe global media services ltd

DVD (digital versatile disc) physical disc format

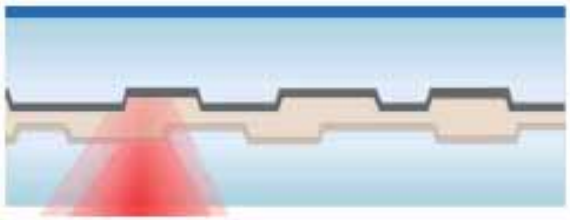
	DVD-5	DVD-9	DVD-10	DVD-18	DVD-R	DVD-RW	DVD-RAM
Capacity (GB[1])	4.7	8.54	9.4	17.08	4.7	4.7	4.7 or 9.4
Layers/side	1	2	1	2	1	1	1
Sides	1	1	2	2	1	1	1 or 2



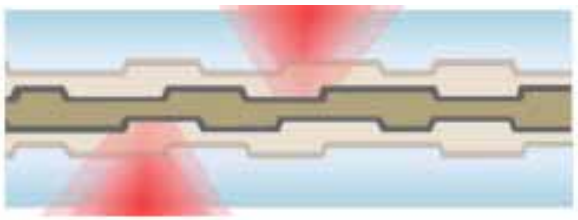
DVD-5 Disc



DVD-10 Disc



DVD-9 Disc



DVD-18 Disc

Recordable/RE-writable DVD Formats

Parameter	Ver 1.0	Authoring use	General use
Capacity (GB)	3.95	4.7	4.7
Recording method	Organic dye layer		
Laser wavelength	635/650nm	635nm	650nm
Min pit length (microns)	0.44	0.40	0.40
Track pitch (microns)	0.80	0.74	0.74
Pre-pit addressing	increment	increment	decrement
Serialisation for CPRM		No	Yes
Track format	Wobble pre-groove		

DVD-R Parameters

Parameter	DVD-RAM Ver 1.0	DVD-RAM Ver 2.1	DVD-RW Ver 1.0
Sides	1 or 2	1 or 2	1
Capacity (GB)	2.6 per side	4.7 per side	4.7 per side
Recording method	Phase change marks		
Track format	Wobble land & groove		Wobble groove
Track pitch (microns)	0.74	0.615	0.74
Min pit length (microns)	0.41	0.28	0.40
Number of zones	24	35	
User data rate (Mb/s)	11.08	22.16	

Parameters for DVD-RAM and DVD-RW

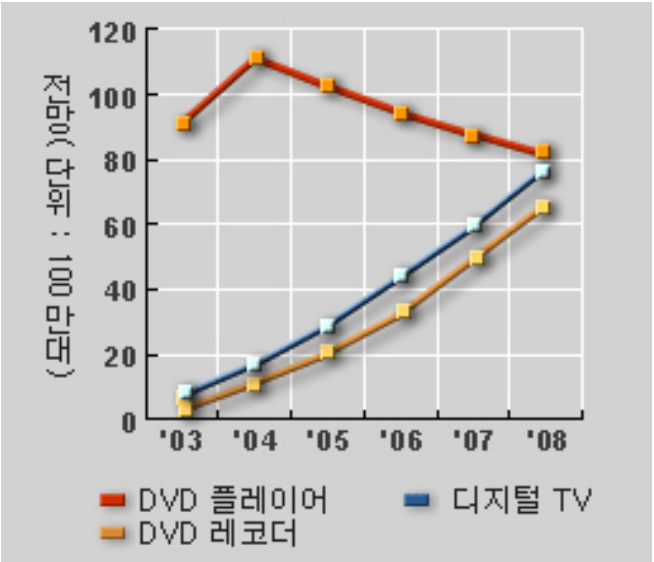
* 출처 : Deluxe global media services ltd

DVD 시장

Year	Steering Committee Members Added
1995	Hitachi, Matsushita, Mitsubishi, Philips, Pioneer, Sony, Thomson, Time Warner, Toshiba and JVC.
1997	IBM, Industry Technology Research Institute (ITRI) of Taiwan, Intel, LG Electronics, NEC, Samsung and Sharp.
2004	Microsoft, Sanyo and Walt Disney.

DVD Forum Steering Committee Members

- 세계 **DVD**시장의 빠른 성장속도 만큼이나 제품가격이 급락하고 있어 단순보급형 제품만으로는 수출을 확대하고 수익성을 극대화하는 데 한계가 있다.
- 현재 국내외 업체들이 주력하고 있는 제품으로는 **DVD**리코더, **DVD**플레이어, 인터넷**DVD**, 게임**DVD**, **DVD**오디오 등과 각각 두 가지 제품을 결합한 **DVD**복합제품 등 다양한 응용제품에 총력을 기울이고 있다.
- 애널리스트들은 **2008**년에는 차세대 **DVD** 플레이어가 **DVD** 레코더와 유사한 시장규모를 형성할 것으로 전망하고 있다.



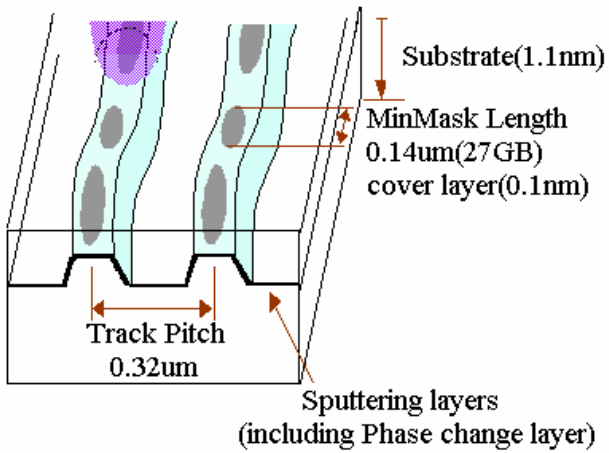
* 출처 : 아이서플라이

Blu-ray (a blue-violet laser to read and write data)

- **What is blu-ray?**
  - **Blu-ray, or Blu-ray Disc (BD) is the name of a next-generation optical disc format jointly developed by the Blu-ray Disc Association (BDA)**
  - **The format was developed to enable recording, rewriting and playback of high-definition video (HD), as well as storing large amounts of data**
- **A single-layer Blu-ray Disc can hold 25GB, which can be used to record over 2 hours of HDTV or more than 13 hours of standard-definition TV. There are also dual-layer versions of the discs that can hold 50GB.**
- **Blu-ray is expected to replace VCRs and DVD recorders over the coming years, with the transition to HDTV**

Blu-ray의 구조 및 특성

- **Track Pitch**는 **0.32㎛**, 최소 기록 마크의 길이는 **0.14㎛**로 기존 **DVD** 포맷의 반 이하 수준이다.
- 기존 **CD**나 **DVD** 계 디스크들이 모두 기판을 통해 레이저 광이 입사됨에 비해 **Blu-ray Disc**는 그 반대편인 커버 층을 통해 입사된다



- **Blu-ray Disc version 1.0 spec**
  - **36Mbps (BD**에 **(25GB)**저장 시 **1**시간 **33**분 소요)
  - **TDK 72Mbps** 데이터 전송속도를 제공하는 **2**배속 디스크를 발표하는 등 꾸준한 기술개발이 이뤄지고 있는 상황이다.
- **Blu-ray Disc format**
  - **BD-ROM**
  - **BD-R**
  - 데이터를 여러 번 반복 기록이 가능한 **BD-RW**
  - **HDTV** 영상을 여러 번 반복 기록이 가능한 **BD-RW** 로 나누어 진다.

Blu-ray와 DVD, HD-DVD와의 차이점

Parameters	BD	BD	DVD	DVD
Storage capacity	25GB	50GB	4.7GB	9.4GB
Number of layers	single-layer	dual-layer	single-layer	dual-layer
Laser wavelength	405nm	405nm	650nm	650nm
Numerical aperture (NA)	0.85	0.85	0.60	0.60
Protection layer	0.1mm	0.1mm	0.6mm	0.6mm
Data transfer rate	36Mbps	36Mbps	11.08Mbps	11.08Mbps
Video compression	MPEG-2 MPEG-4 AVC VC-1	MPEG-2 MPEG-4 AVC VC-1	MPEG-2	MPEG-2

Blu-ray vs DVD

Parameters	BD	BD	HD-DVD	HD-DVD
Storage capacity	25GB	50GB	15GB	30GB
Number of layers	single-layer	dual-layer	single-layer	dual-layer
Laser wavelength	405nm	405nm	405nm	405nm
Numerical aperture (NA)	0.85	0.85	0.65	0.65
Protection layer	0.1mm	0.1mm	0.6mm	0.6mm
Data transfer rate	36Mbps	36Mbps	36Mbps	36Mbps
Video compression	MPEG-2 MPEG-4 AVC VC-1	MPEG-2 MPEG-4 AVC VC-1	MPEG-2 MPEG-4 AVC VC-1	MPEG-2 MPEG-4 AVC VC-1

HD-DVD is the name of a competing next-generation optical disc format developed by Toshiba and NEC. The format is quite different from Blu-ray, but also relies heavily on blue-laser technology to achieve a higher storage capacity

Blu-ray 제조 업체

- **Blu-ray recorders**
  - Hitachi
    JVC
    LG
    Mitsubishi
    Panasonic
    Philips
    Pioneer
    Samsung
    Sharp
    Sony
    Zenith

SAMSUNG

Sony

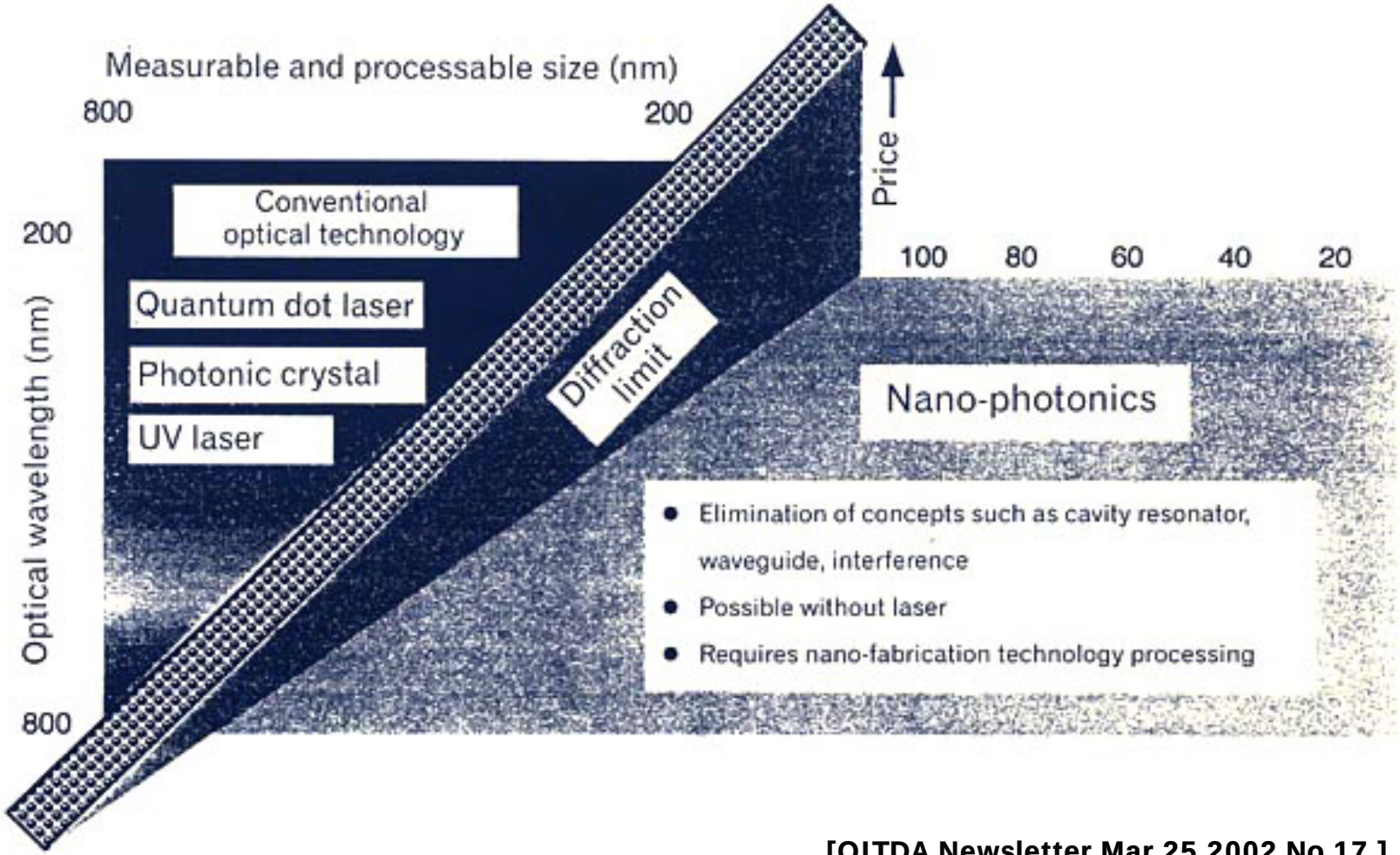
- **Blu-ray media**
  - Fujifilm
    JVC
    Maxell
    Mitsubishi
    Panasonic
    Samsung
    Sony
    TDK

SAMSUNG

Sony

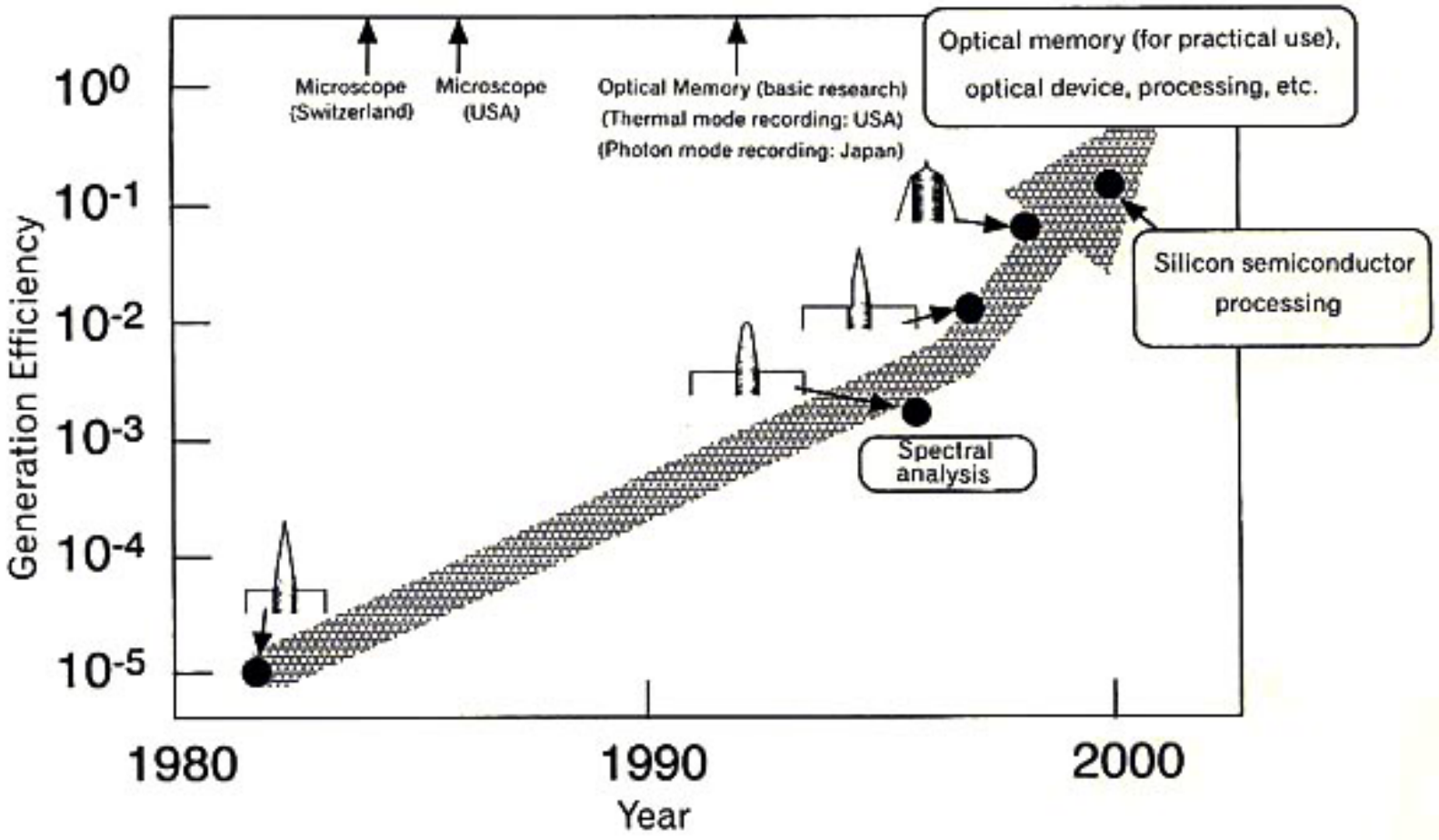
Fujifilm

Paradigm Shift Provoked by Nano-photonics



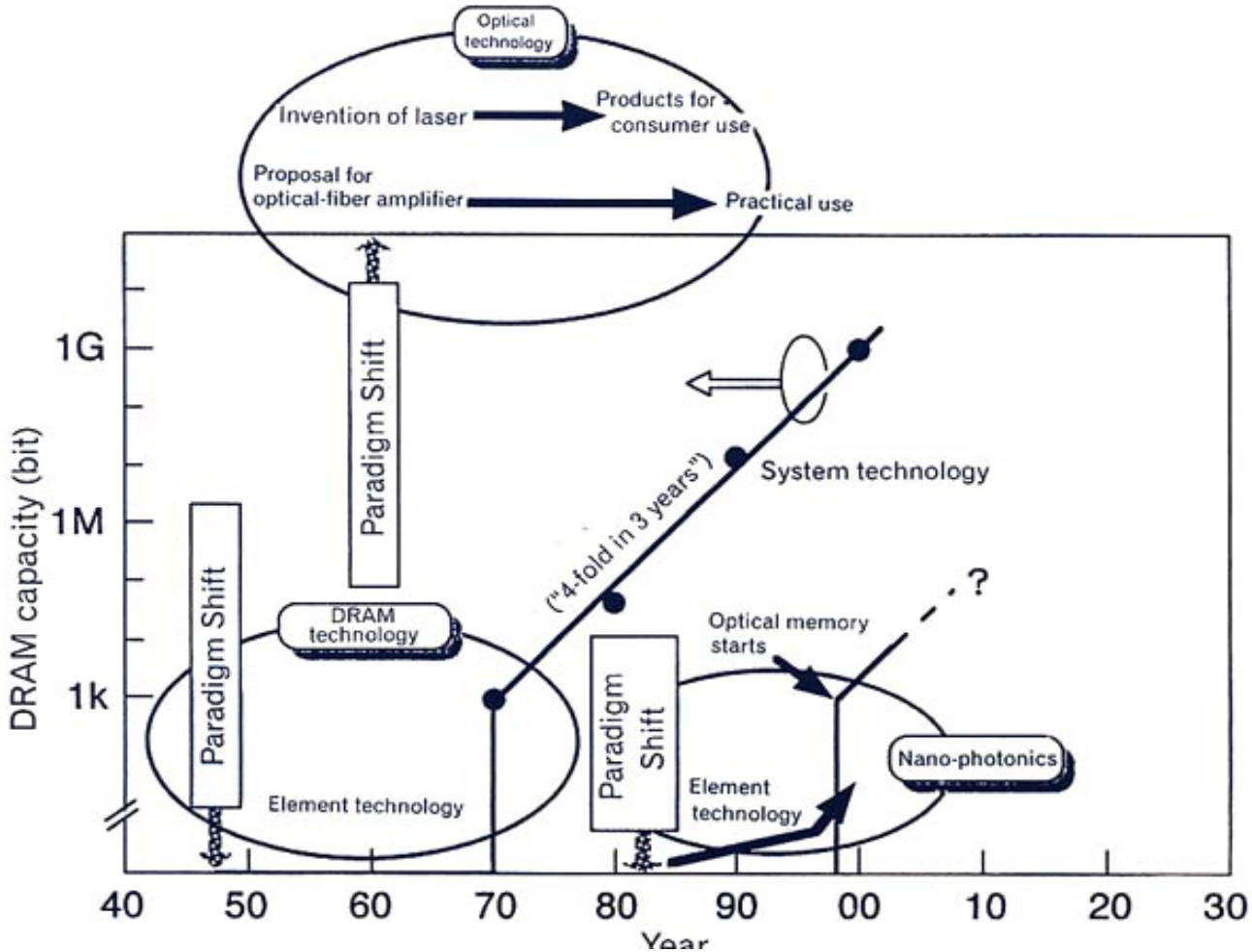
[OITDA Newsletter Mar 25,2002 No.17]

Progress of Optical Near-Field Generation Efficiency of Fiber Probe



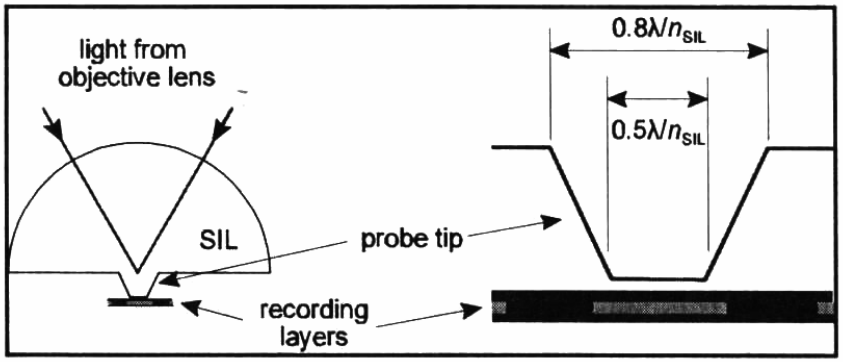
[OITDA Newsletter Mar 25,2002 No.17]

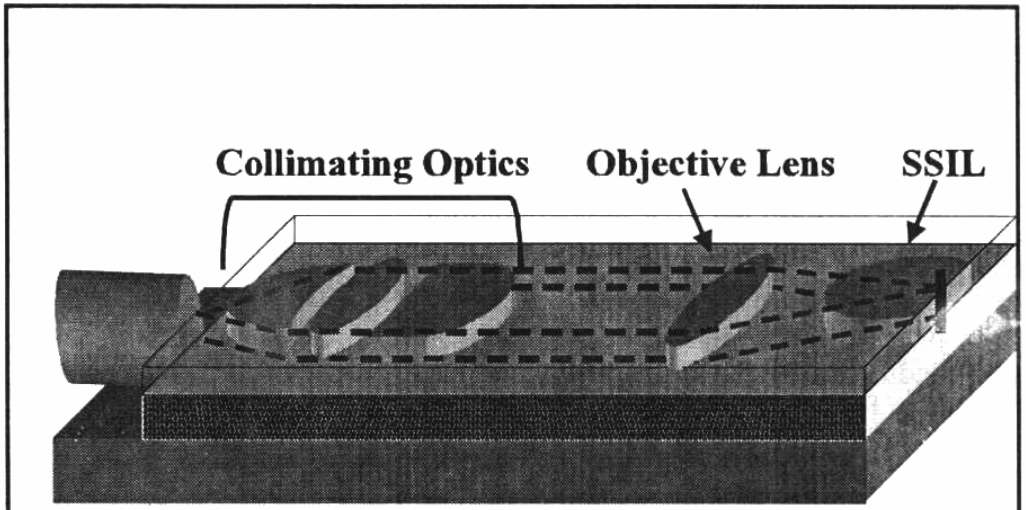
Chronological Comparison of Nano-photonics, DRAM Technology, and Optical Technology



[OITDA Newsletter Mar 25,2002 No.17]

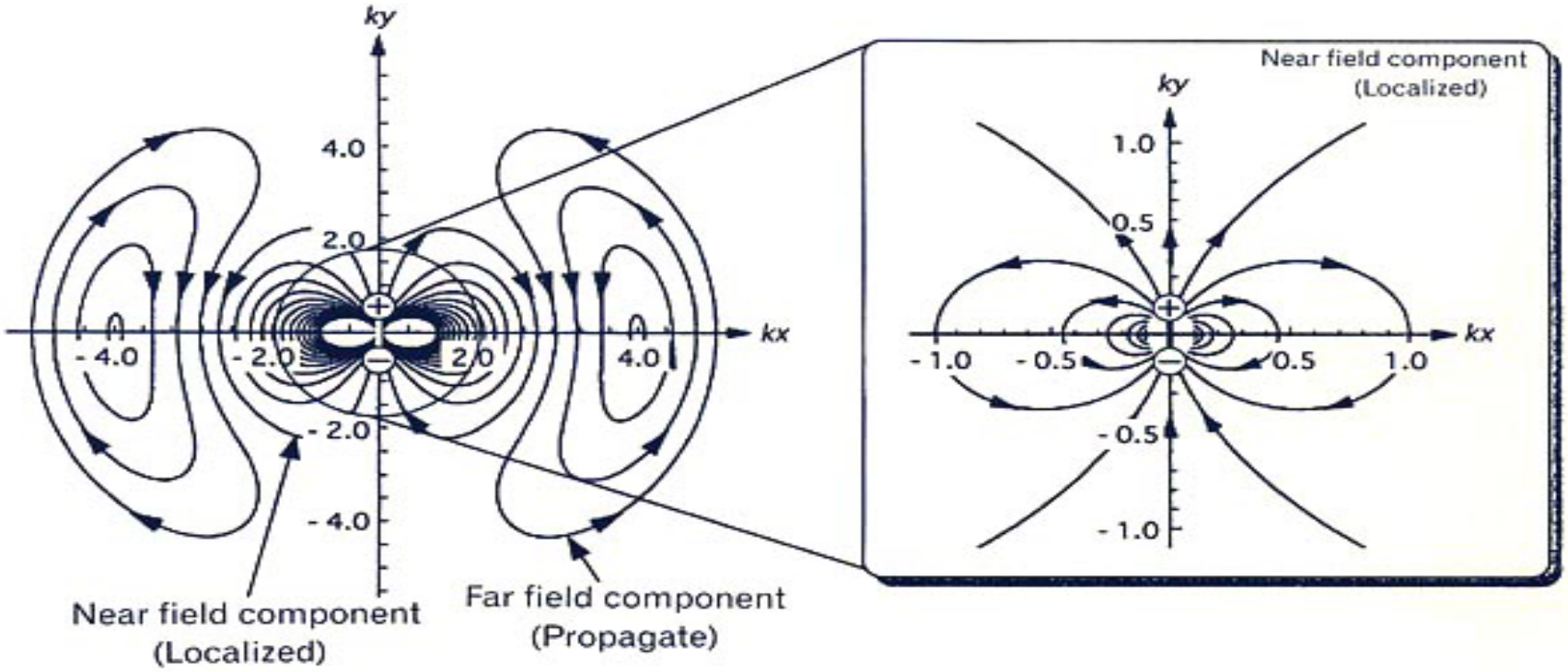
Near-field Optical Data Storage





- Waveguide is coupled to optical fiber/laser diode
- Multiple or single lens elements may be used
- Focusing of the beam occurs in the plane of the waveguide only
- Dimensions of optical line are ~800nm x *s*

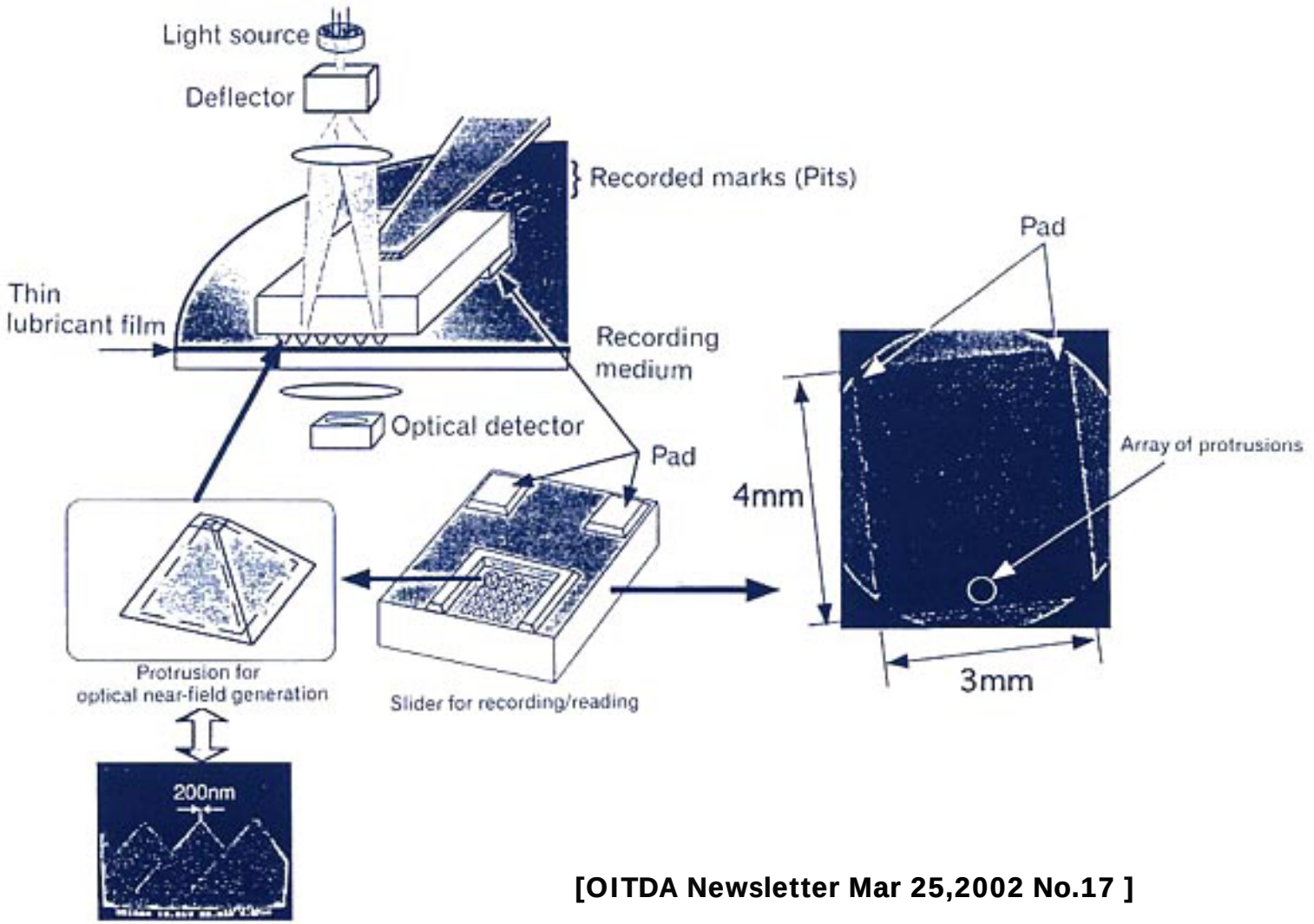
Near field recording



Two Kinds of Electric Lines of Force of Electromagnetic Field Generated by Oscillating Electric Dipole

[OITDA Newsletter Mar 25,2002 No.17]

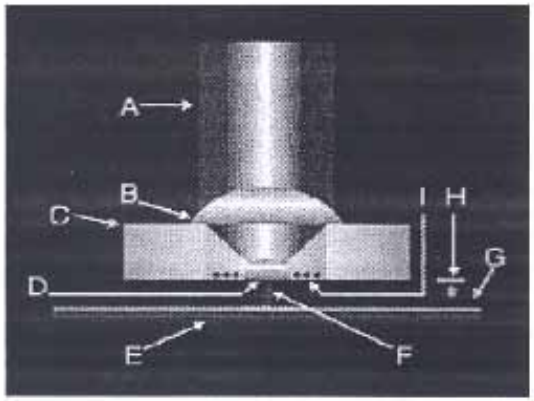
A Method of Near-Field Optical Recording/Reading Using Silicon Protrusion



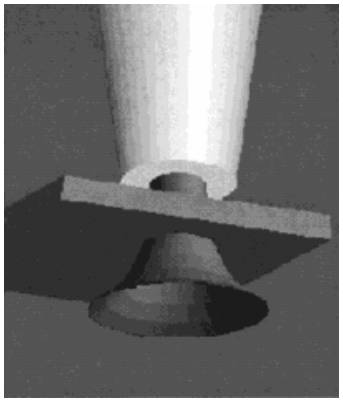
[OITDA Newsletter Mar 25,2002 No.17]

Next Generation Optical Data Storage

- Solid Immersion Lens

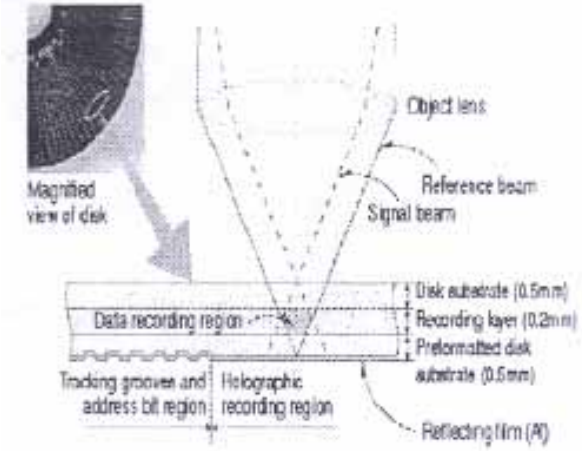


- Scanning prove method

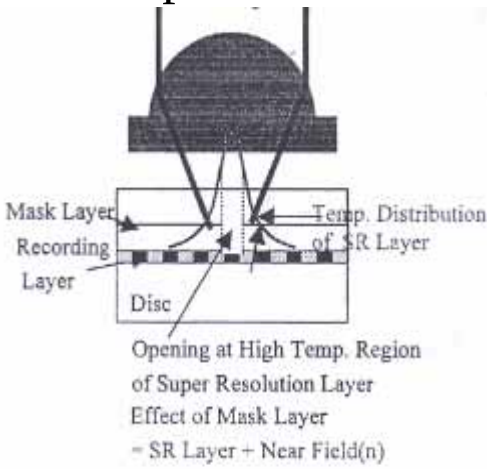


* Chem. Rev. 1999. 99. 2891-2927

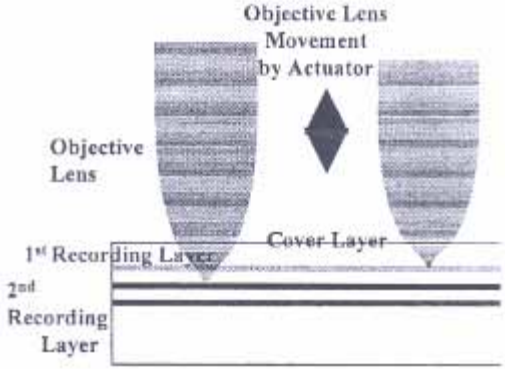
- Holographic Memory



- Super-RENS



- Multi-Layer Recording



* 2005 Topical Meeting on Nano-Optical Probe

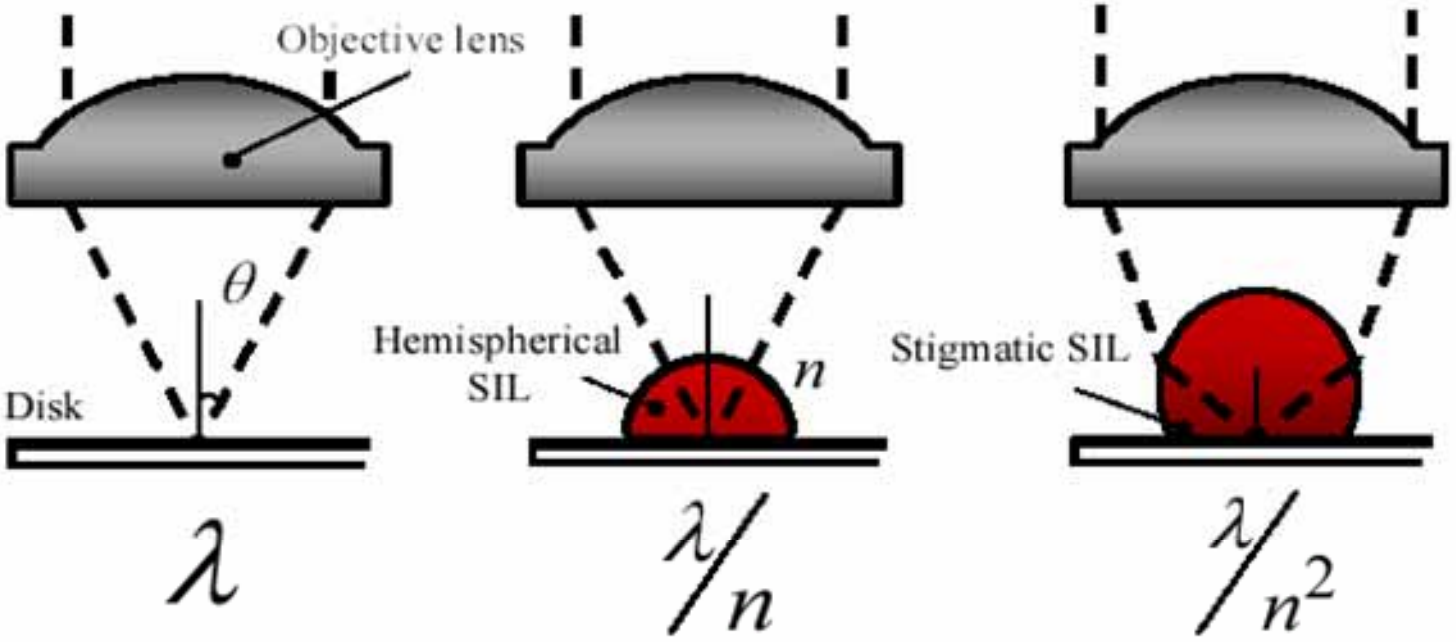
Near Field Optical Readout Using a Solid Immersion Lens (SIL)

reduce the size of the focused spot below the diffraction limit

image through a material of high refractive index n

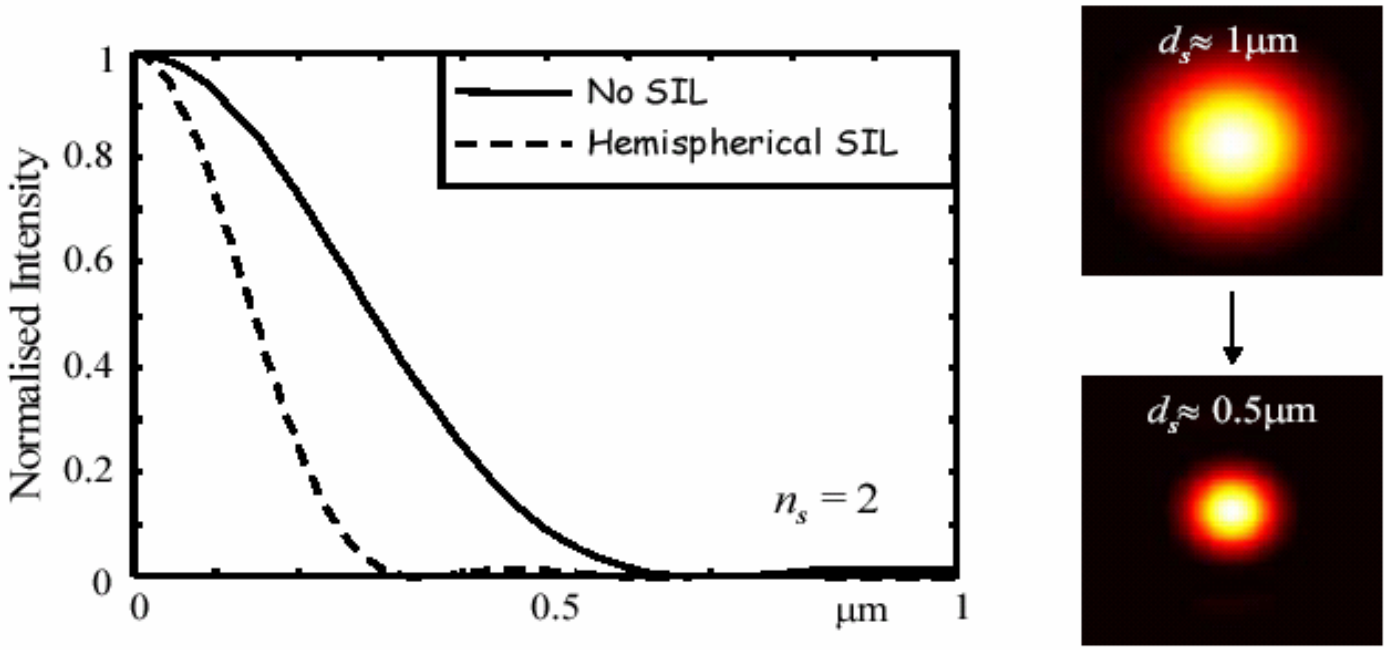
$\lambda \Rightarrow \lambda/n$

image through a hemispherical lens

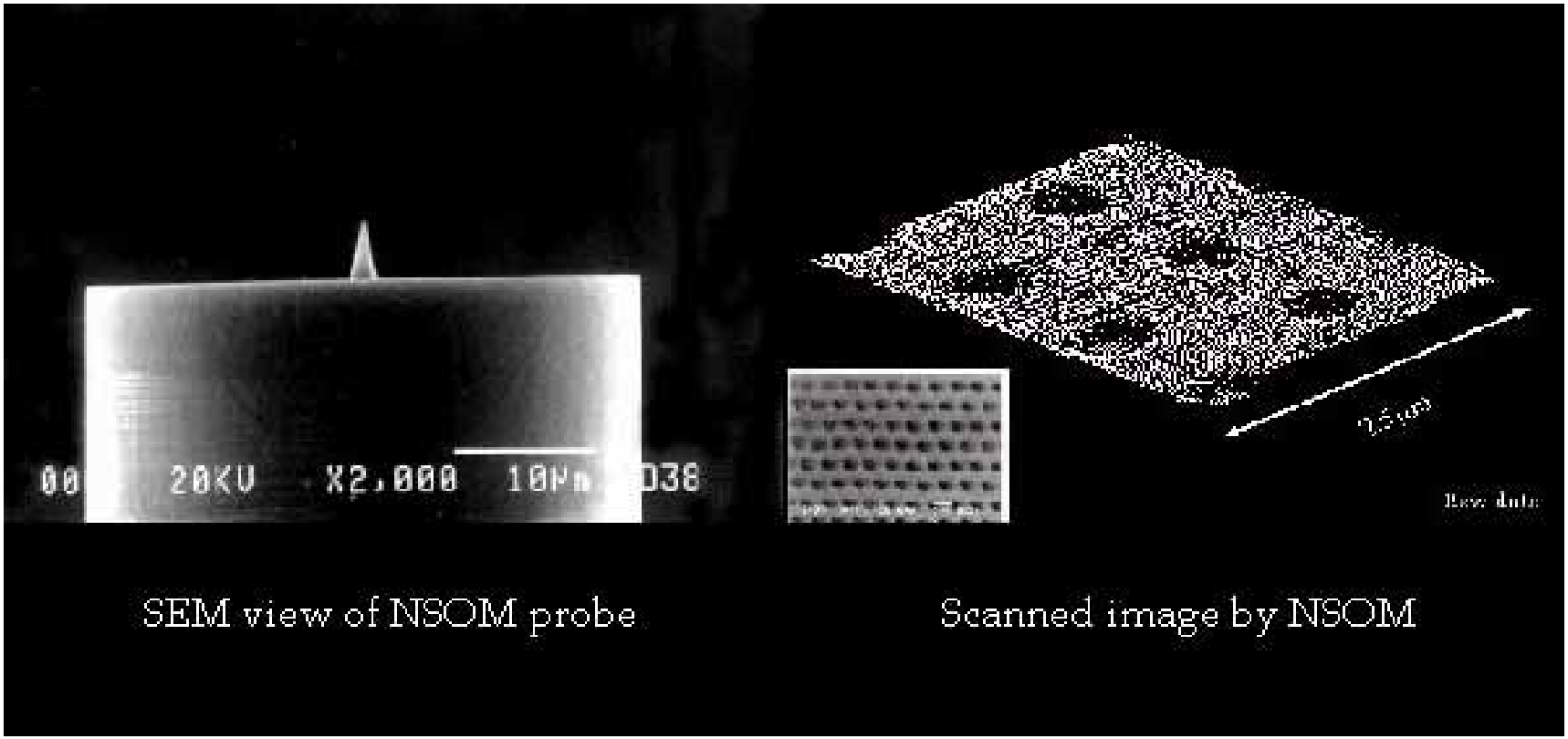


Near Field Imaging

Readout Predicted Using an Optical Readout Model

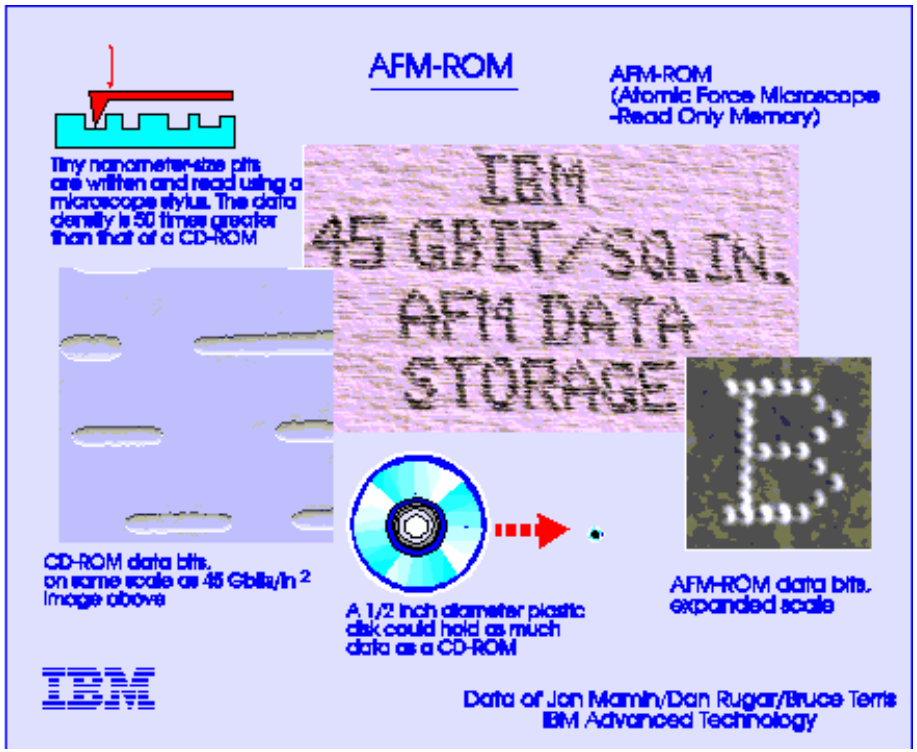


Near-field Scanning Optical Microscope (NSOM)



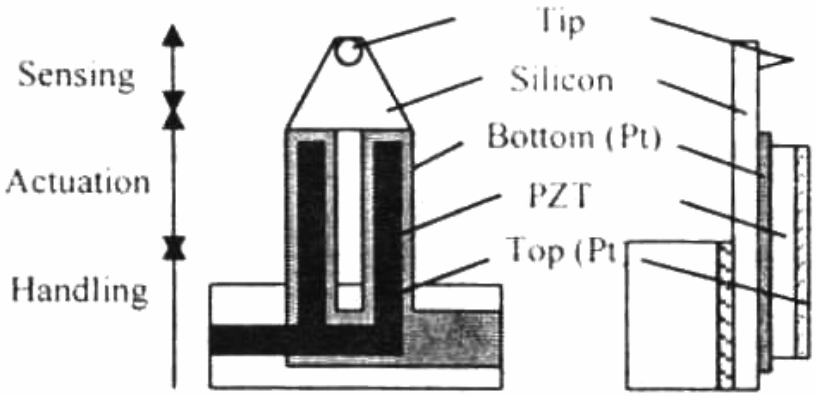
Scanning Probe Methods

AFM-ROM

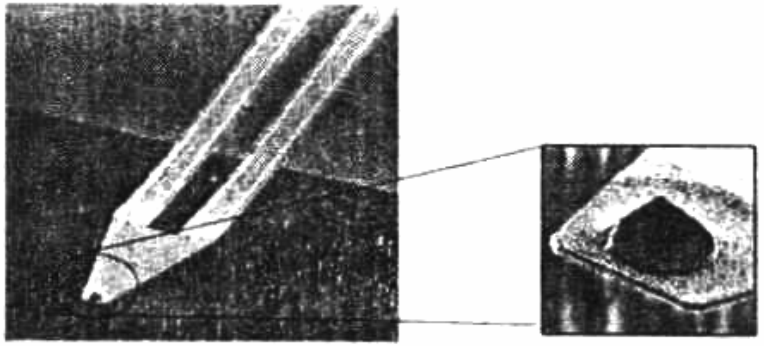


addr : www.almaden.ibm.com/storage/technolo /grochows/grocho18.html

Use of Scanning Probes



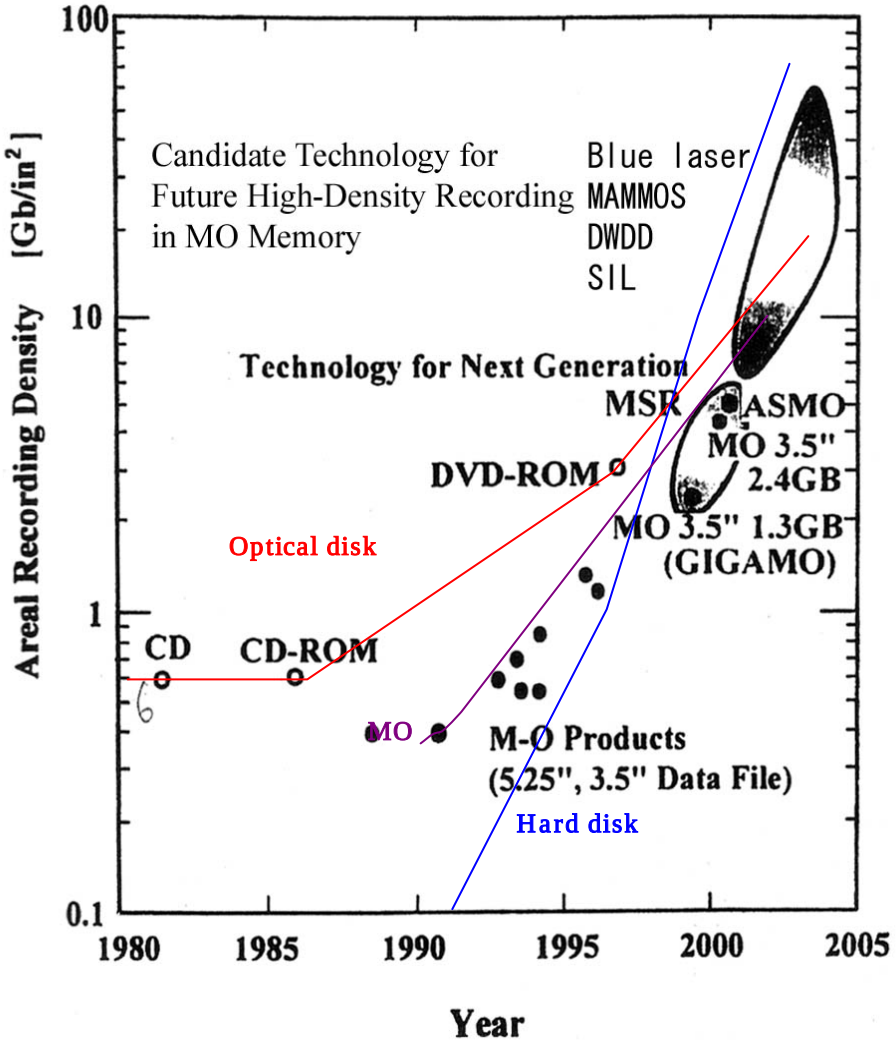
(a)



(b)

Magneto-optical Disc

Increase of Areal Density in Optical Disks



T. Suzuki:113th Topical Meeting of Magn. Soc. Jpn. (2000.1) p.11

Different Disks

MO（magneto-optical）Recording

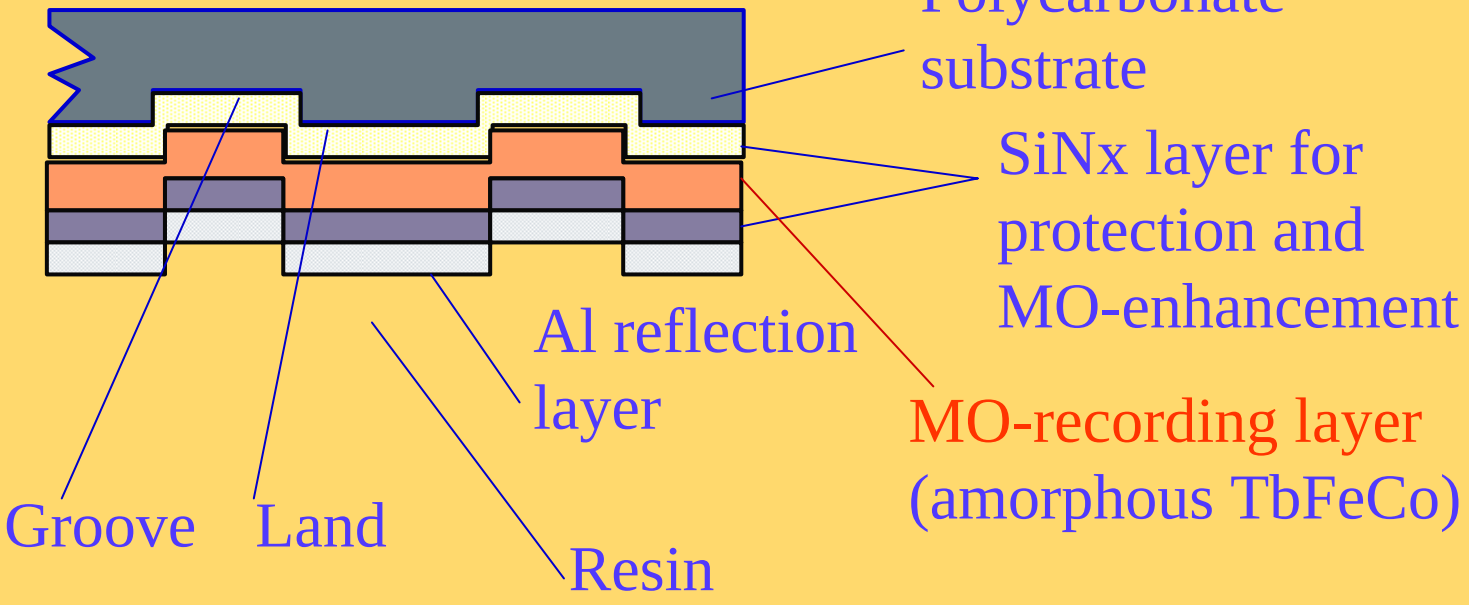
- **Recording：Thermomagnetic (Curie point）recording**
  - **Heat-assisted magnetic recording**
- **Playback：Magneto-optical effect**
  - Rotation of linear polarization is converted to the electrical signal
- Employed in MO, MD **disks**
- **Compatibility**
- **High repeatability**：10,000,000 times
- **Complicated optical head (Polarization detection）**
- Novel inventions such as MSR, MAMMOS, DWDD are realized as commercial products

History of MO recording

- 1962 Conger,Tomlinson Proposal for MO memory
- 1967 Mee Fan Proposal of beam-addressable MO recording
- 1971 Argard (Honeywel) MO disk using MnBi films
- 1972 Suits(IBM) MO disk using EuO films
- 1973 Chaudhari(IBM) Compensation point recording to a-GdCo film
- 1976 Sakurai(Osaka U) Curie point recording on a-TbFe films1980 Imamura(KDD) Code-file MO memory using a-TbFe films
- 1981 Togami(NHK) TV picture recording using a-GdCo MO disk
- 1988 Commercial appearance of 5”MO disk (650MB)
- 1889 Commercial appearance of 3.5 ”MO disk(128MB)
- 1991 Aratani(Sony) MSR
- 1992 Sony MD
- 1997 Sanyo ASMO(5” 6GB：L/G, MFM/MSR) standard
- 1998 Fujitsu GIGAMO(3.5” 1.3GB)
- 2000 Sanyo, Maxell iD-Photo(5cmϕ730MB)
- 2004 Sony Hi-MD

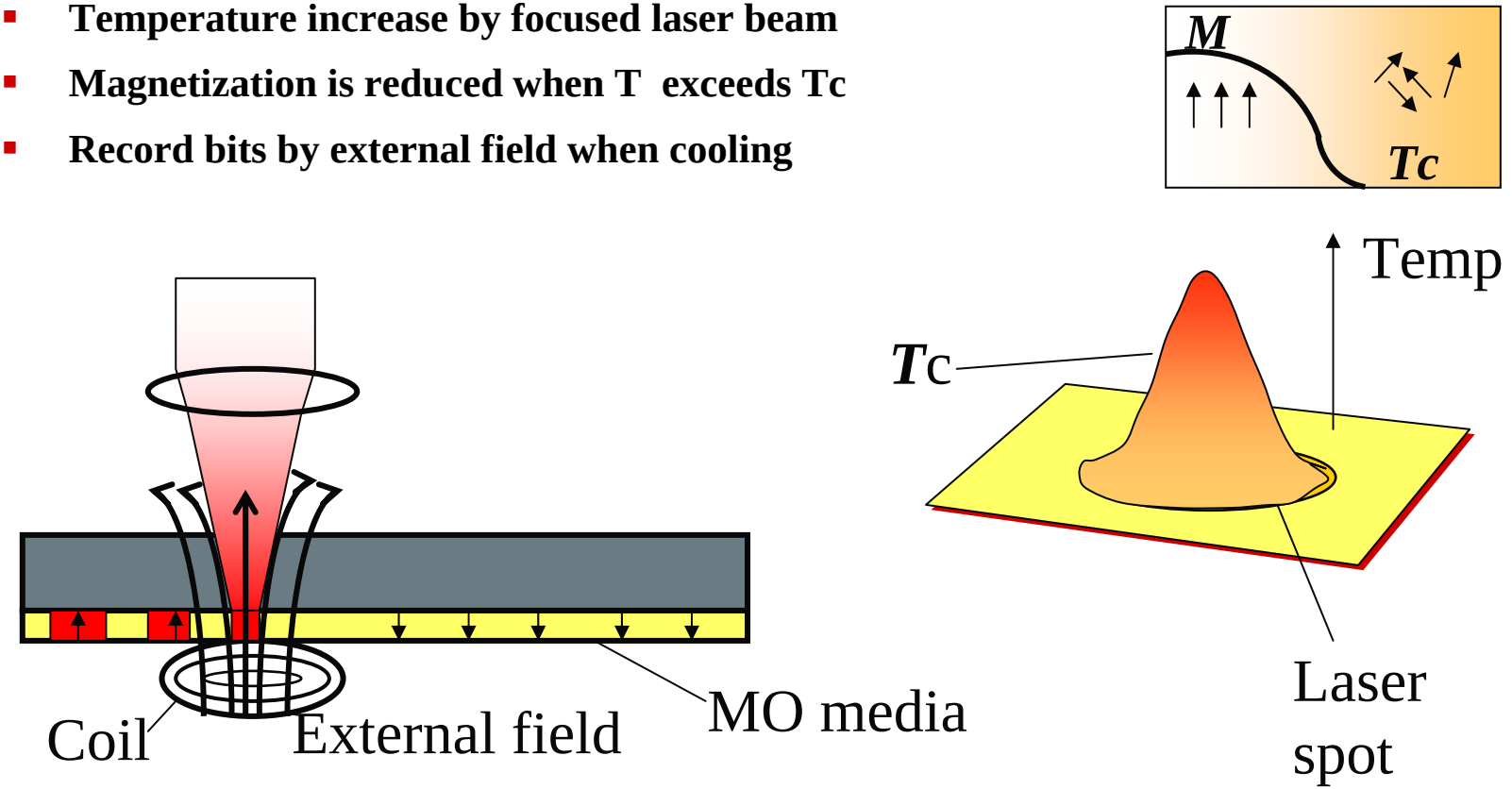
Structure of MO disk media

- **MO disk structure**



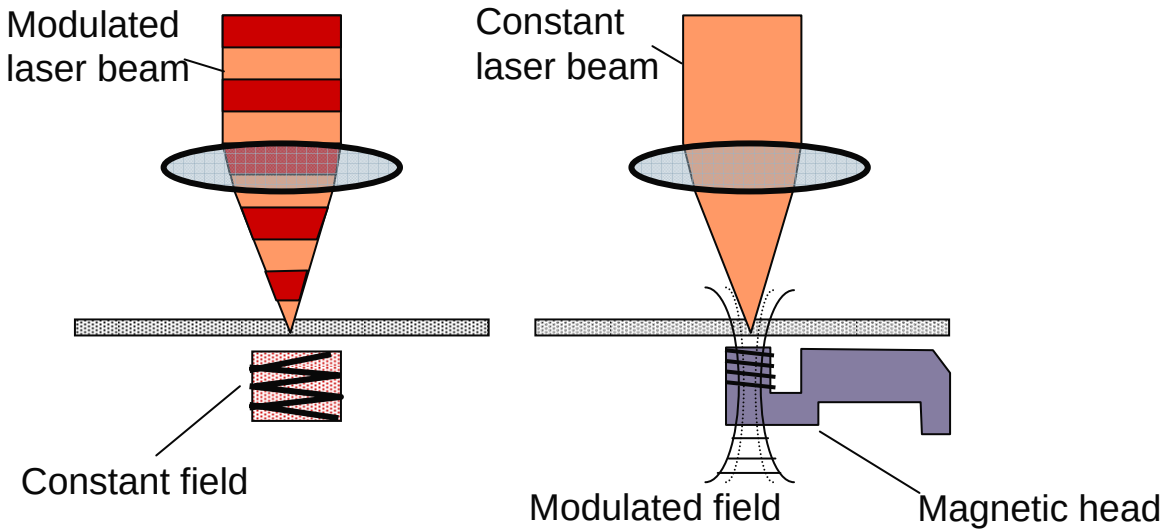
MO recording How to record

- Temperature increase by focused laser beam
- Magnetization is reduced when T exceeds Tc
- Record bits by external field when cooling



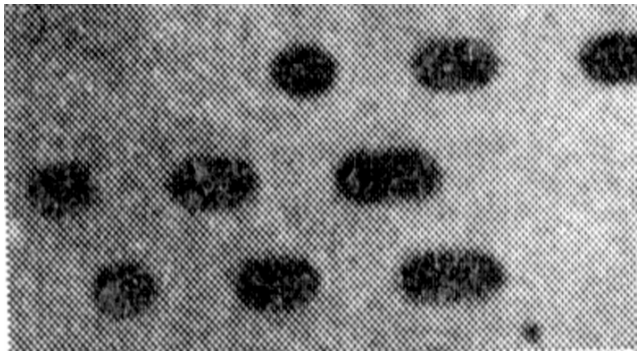
Two recording modes

- **Light intensity modulation (LIM) : present MO**
  - Laser light is modulated by electrical signal
  - Constant magnetic field
  - Elliptical marks
- **Magnetic field modulation (MFM) : MD, ASMO**
  - Field modulation by electrical signal
  - Constant laser intensity
  - Crescent-shaped marks



(a) LIM (b) MFM

Shape of Recorded Marks

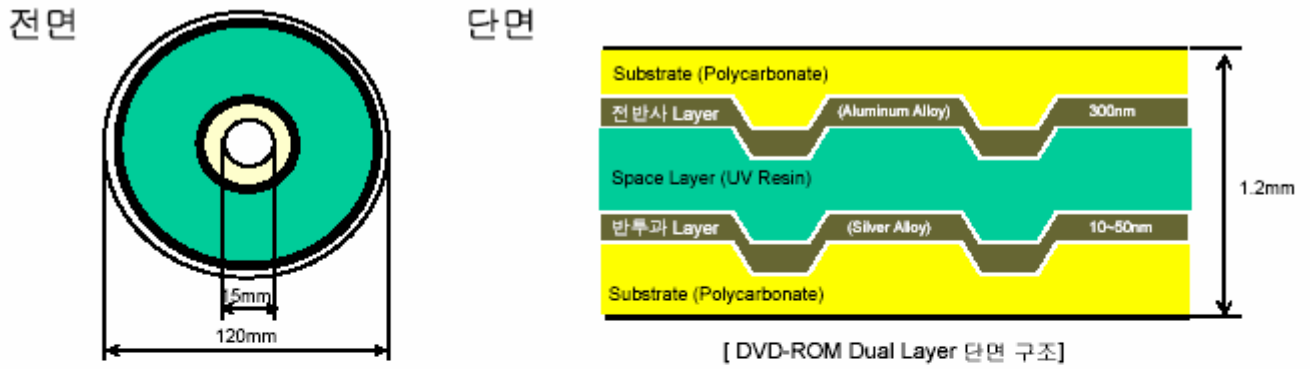


(a) LIM (light intensity modulation)

(b) MFM (magnetic field modulation)

광디스크

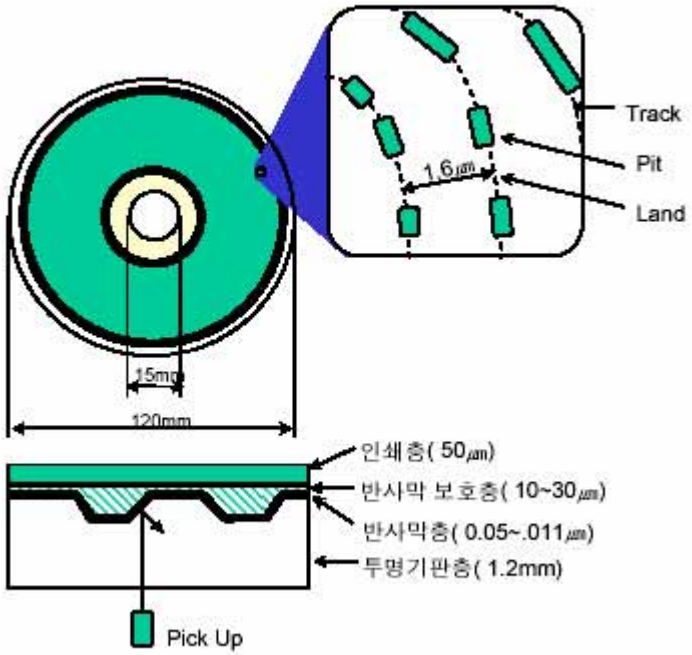
광디스크 기본 구조[재생용]



[DVD-ROM Dual Layer 단면 구조]

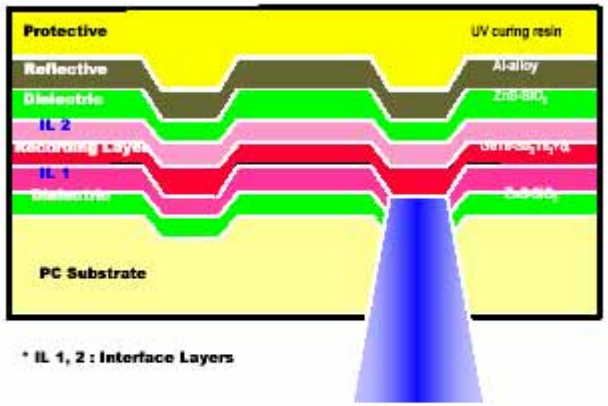
광디스크 기본 구조[기록용]

재생 전용 **Disc** 구조

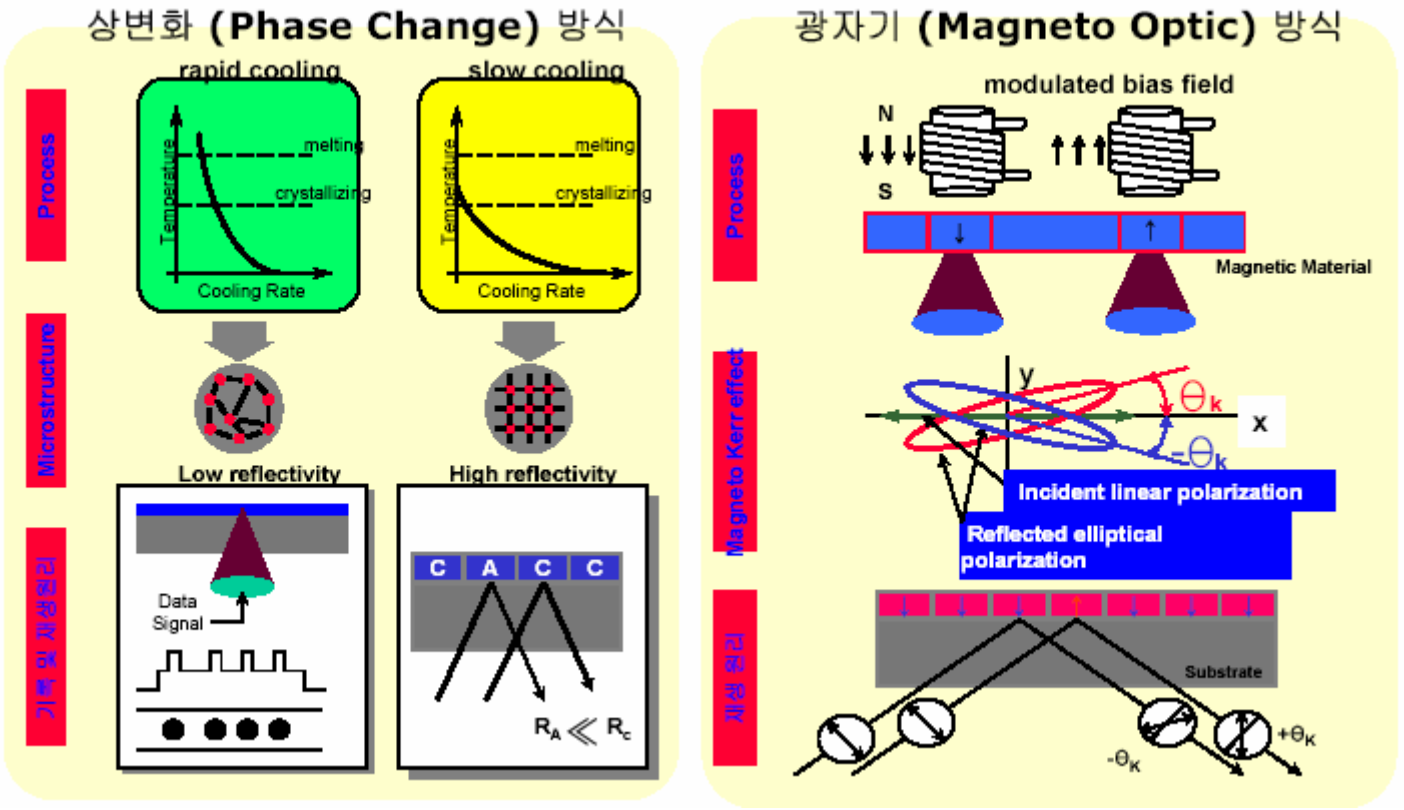


CD-ROM Disc 의 경우

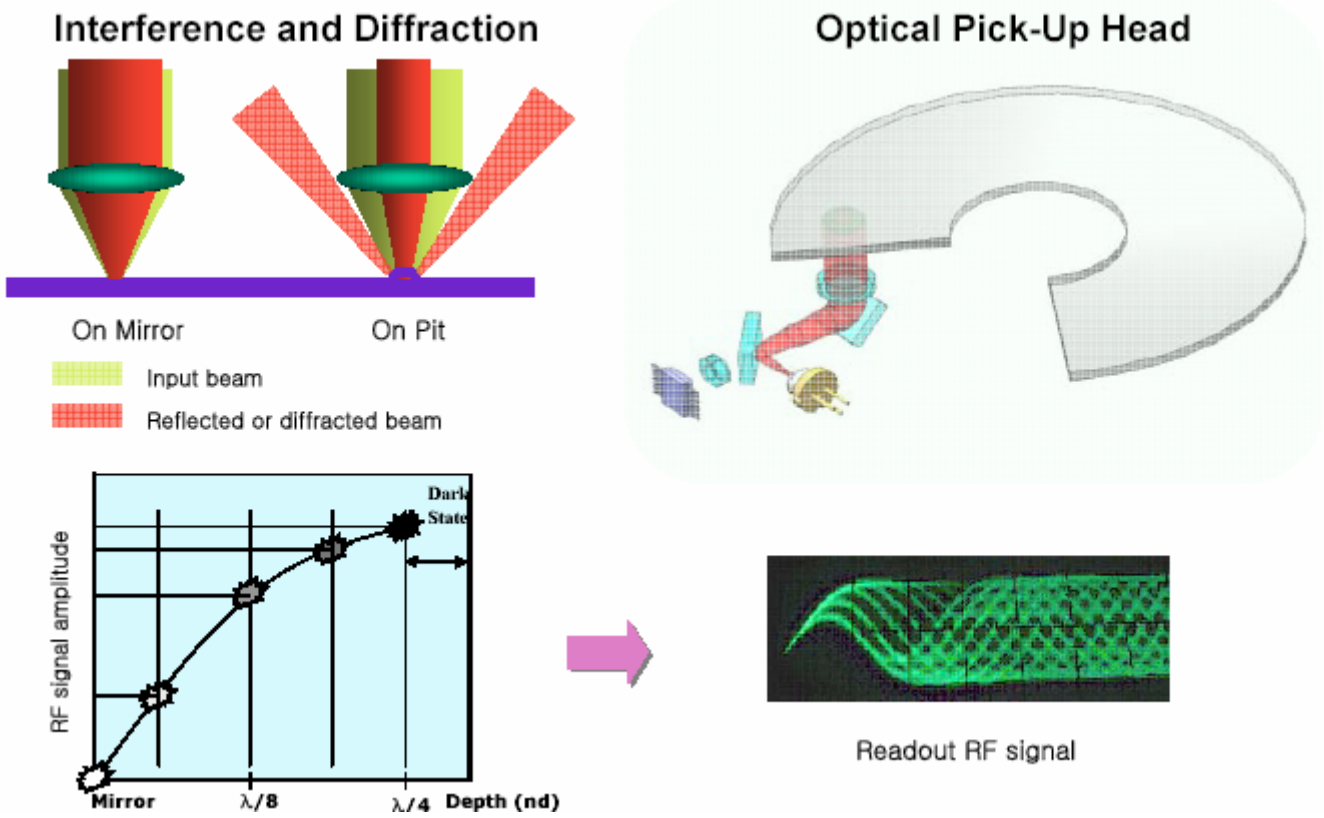
기록용 **Disc** 구조



Re-writable 기록 방식

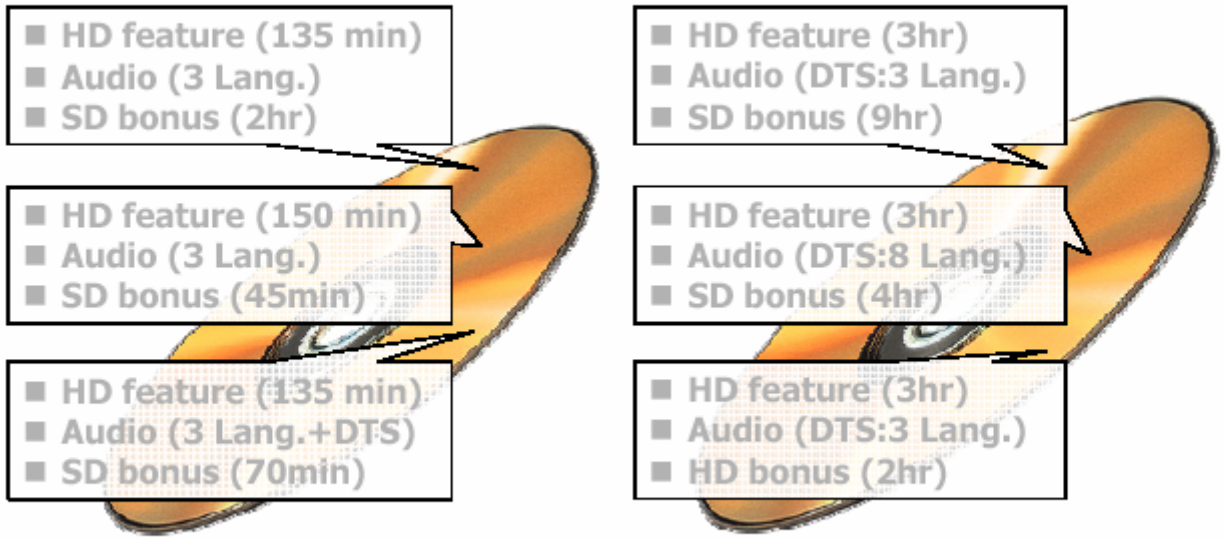


광 디스크 재생 원리


Interference and Diffraction
On Mirror
On Pit
Input beam
Reflected or diffracted beam
RF signal amplitude
Mirror
λ/8
λ/4
Depth (nd)
Optical Pick-Up Head
Readout RF signal

BD-ROM capacity

■ 대 기록 용량은 고화질 영화 및 보너스 영상제공이 가능



Single layer BD-ROM (25GB)

Dual layer BD-ROM (50GB)

규격 비교

❑ 현재 Blu-ray 진영, HD DVD 진영 모두 기본 배속의 물리 규격을 완료한 상태에서,
Audio/Video Application 규격 및 Contents Protection 규격 작업을 진행 중에 있음.

	Blu-ray Disc	HD DVD
용량	• ROM 25/50 GB, R 25/50 GB, RE 25/50 GB	• ROM 15/30 GB, R 15/(30) GB, RW 20 GB
장점	• 저장 용량 : HD-DVD 대비 10G 이상 우세, HD 방송 녹화용 적합 • 추진 업체 : 대형 AV 업체 및 다수 ODD 업체 • PC 업체 : Dell, HP, Apple 등 주요 업체 지지	• CD/DVD 호환성 개발 우위 • 영화 Title 생산 면에서 기존 DVD 설비 개조 이용 가능 • PC 업체 : NEC, Toshiba
기술 특성	• Disc 기록 층 두께 : 0.1 mm • Video 압축 Format : MPEG2, H.264, VC-1 • Interactivity: BD-Java	• Disc 기록 층 두께 : 0.6 mm (DVD와 동일) • Video 압축 Format : MPEG2, H.264, VC-1 • Interactivity: iHD
참여 업체	• BoD 16C* (기존 14C에 Disney / Apple join) • BDA : '04.10 출범 시 75개 사에서 146개 사로 증가 • Contents 업체 : Sony Pic., MGM, Fox, Disney	• Toshiba, NEC, Time Warner, Sanyo 중심 • DVD Forum 내 WG 에서 규격 논의 진행 • Contents 업체 : Time Warner 주도 Universal, Paramount
출시 시점	• BD-RE Drive: '05. Q4~'06.Q1 출시 예상 • BD Recorder/Player: '06.Q1 ~Q2 출시 예상 • Game 기 (PS3) : '06.3월 출시 예상	• HD DVD ROM Drive: '05.Q4 출시 예상 • HD DVD Player: '05. 末 (일본) / '06.Q1 (미국) • Game 기 : '06. 末 ??

* BoD 16C : Sony, Philips, Matsushita, LG, Samsung, Pioneer, Hitachi, Sharp, Thomson (9C)
HP, Dell, Mitsubishi, TDK, Fox, Disney, Apple (9C →16C)

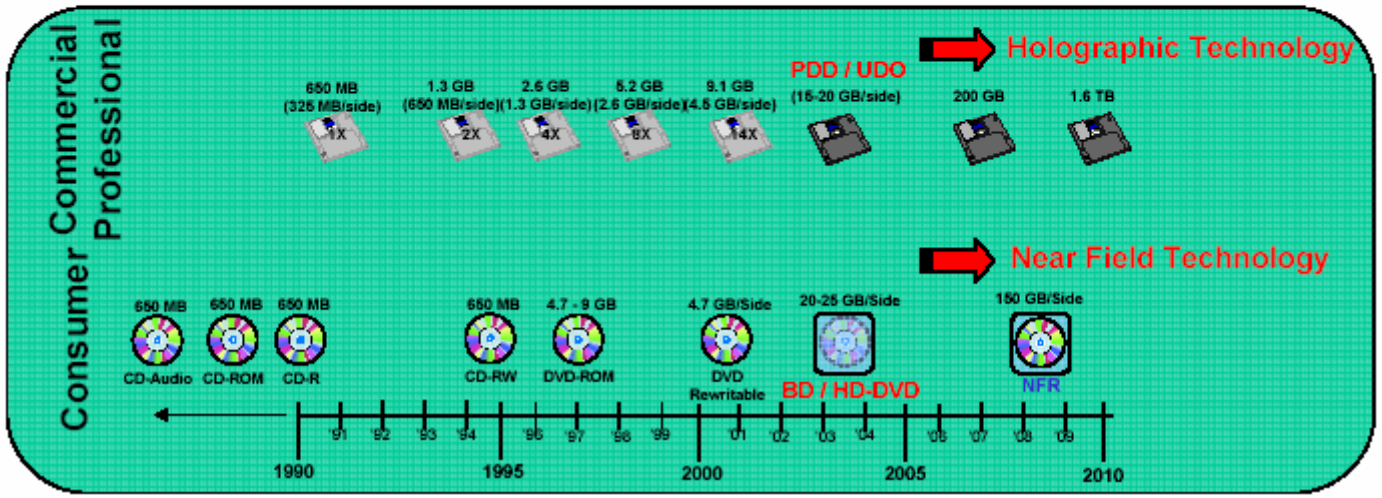
차세대 **storage** 기술

❑ 차세대 Storage 기술 개요 및 시장 전망

NFR 기술
- 고용량 (300GB급)
- ROM 제작이 용이
- Consumer Product 가능하여 BD 이후의 고용량 CE 제품화 target

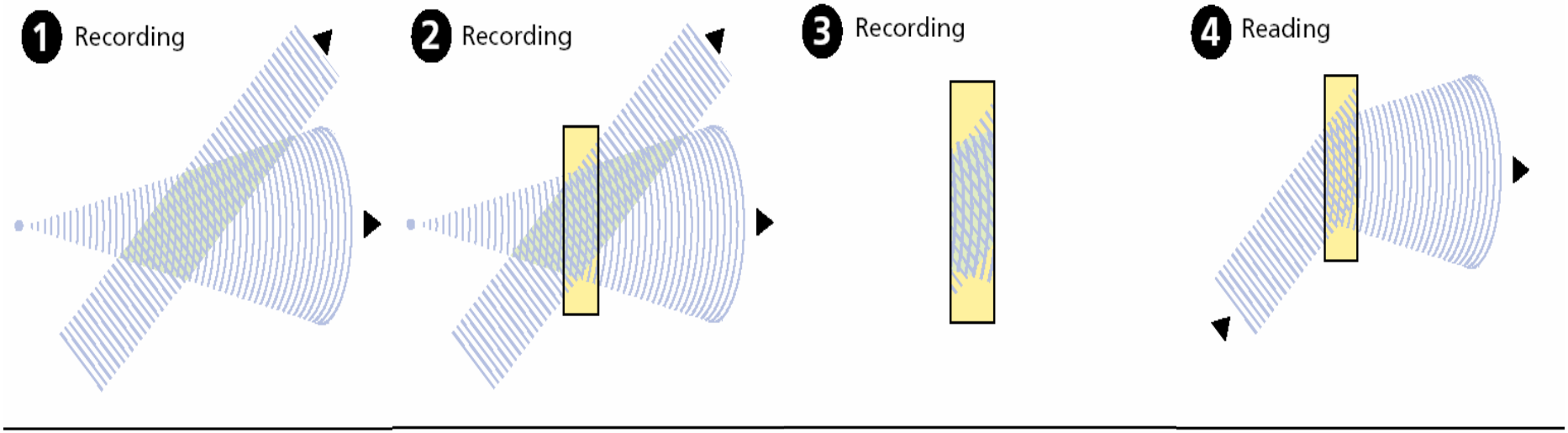
ODD Needs
- 현 Optical Storage 가격 경쟁력 악화 시장 포화 현상 조짐
- 고부가가치, 고 용량, 고안정성을 갖는 새로운 기술과 시장 개척으로 사업 경쟁력 강화 필요

Holography Storage 기술
- -고용량 (200GB →1.6TB 목표)
- 빠른 정보 전송률 (20 MB/s → 120MB/s)
- 긴 보존 기간 (50년 이상)
- Professional Market 적합

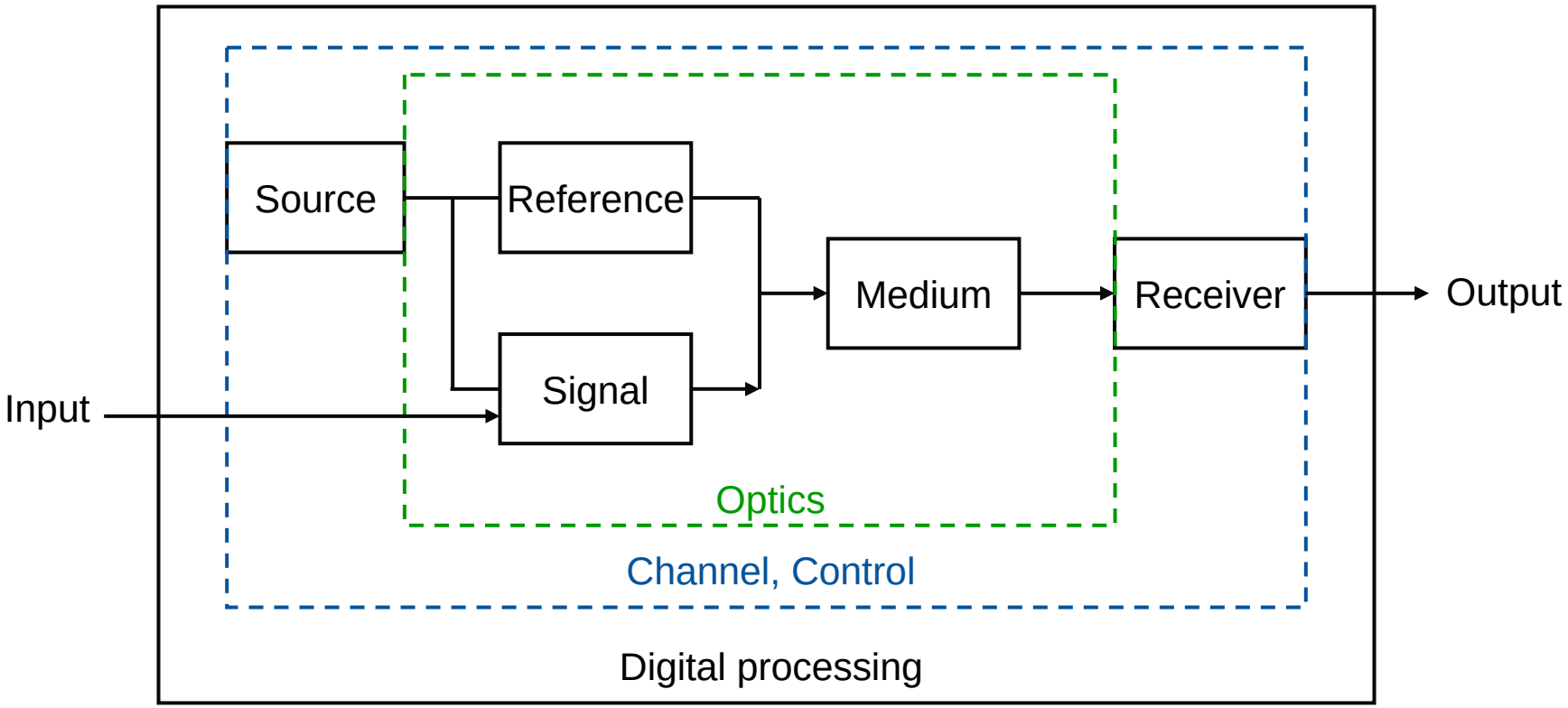


홀로그래픽 데이터 스토리지 시스템 소개

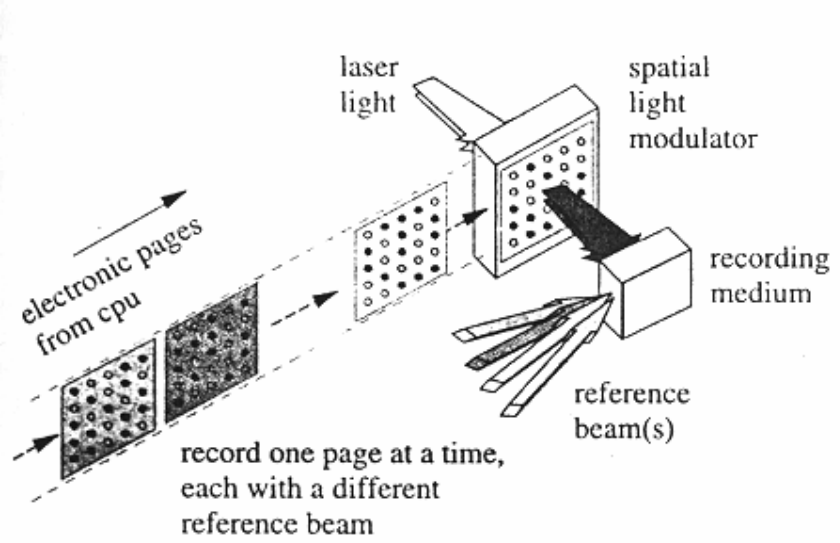
Holography: *'whole recording'*

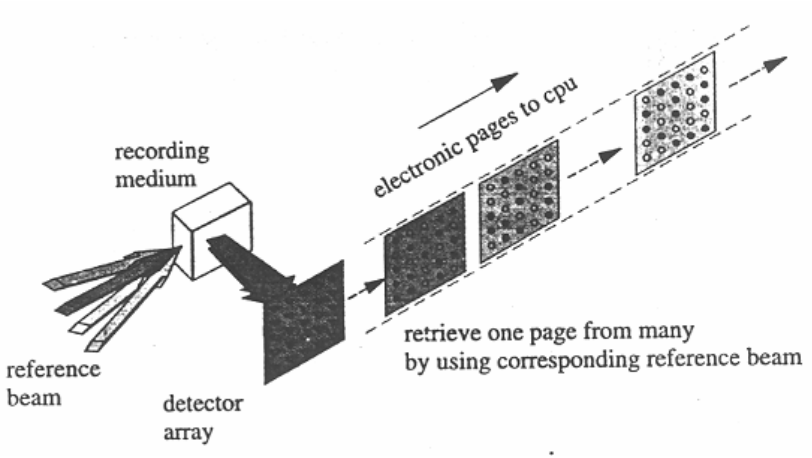


HDS scheme


Source
Reference
Medium
Receiver
Output
Input
Signal
Optics
Channel, Control
Digital processing

Multiplexing





Recording

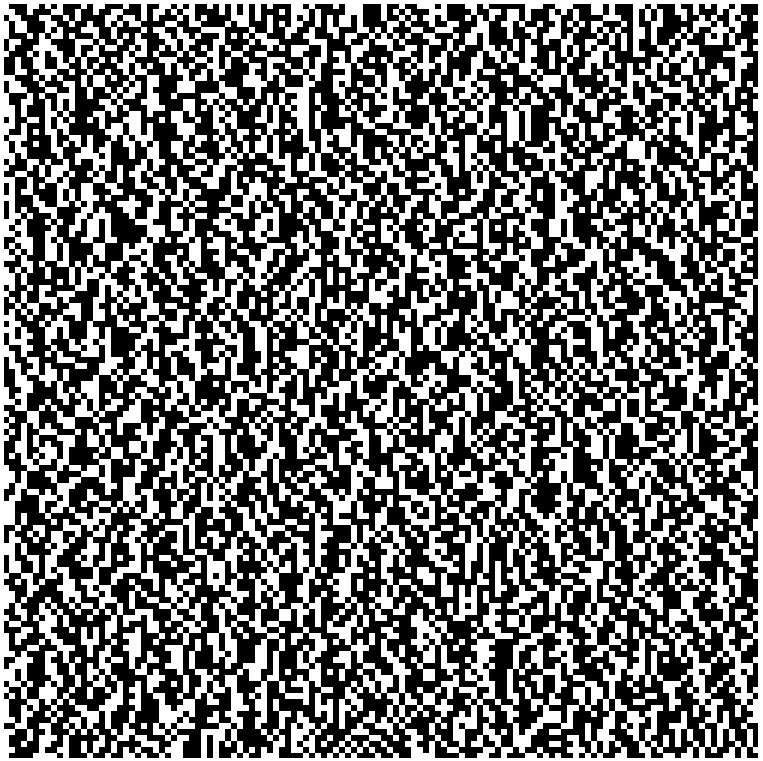
Reading

- Parallel access to data
- Multiple data in one location

→

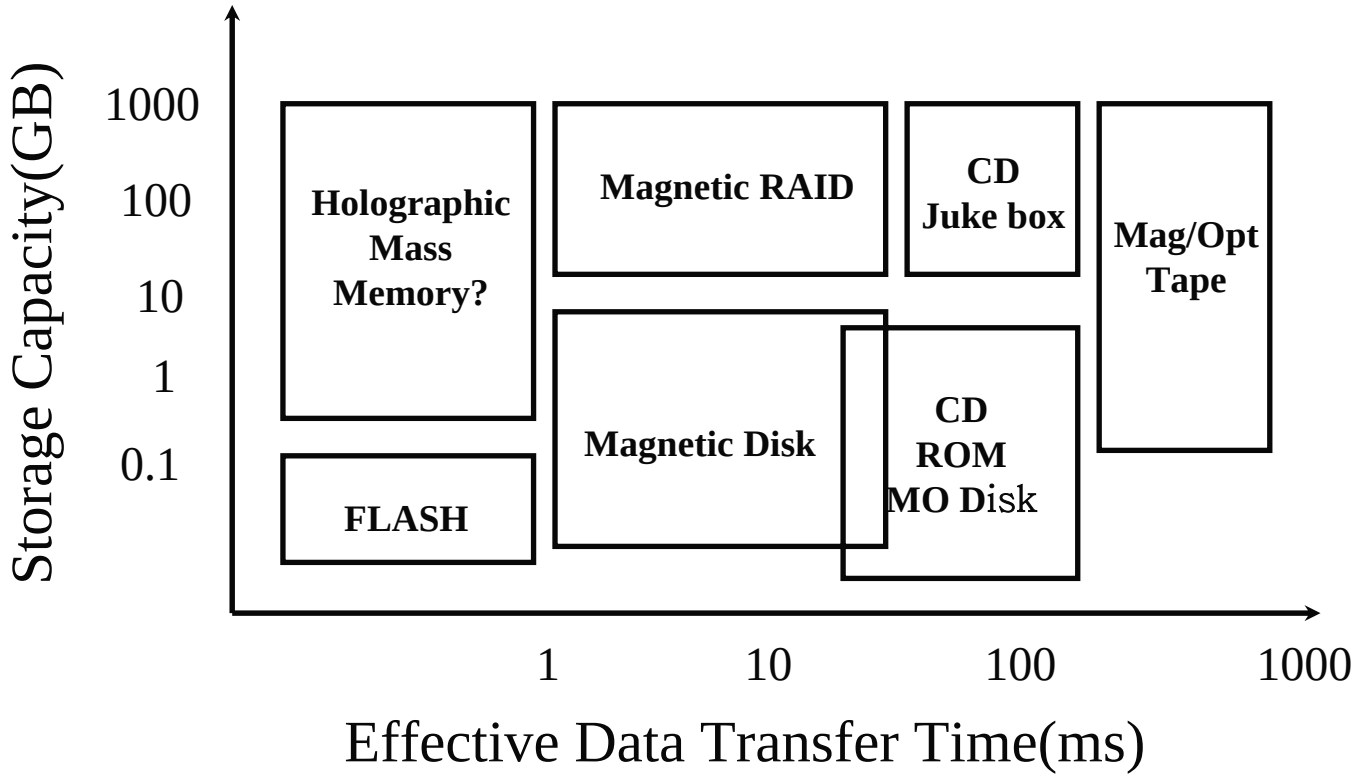
- Fast data transfer rate
- High storage density

Data page

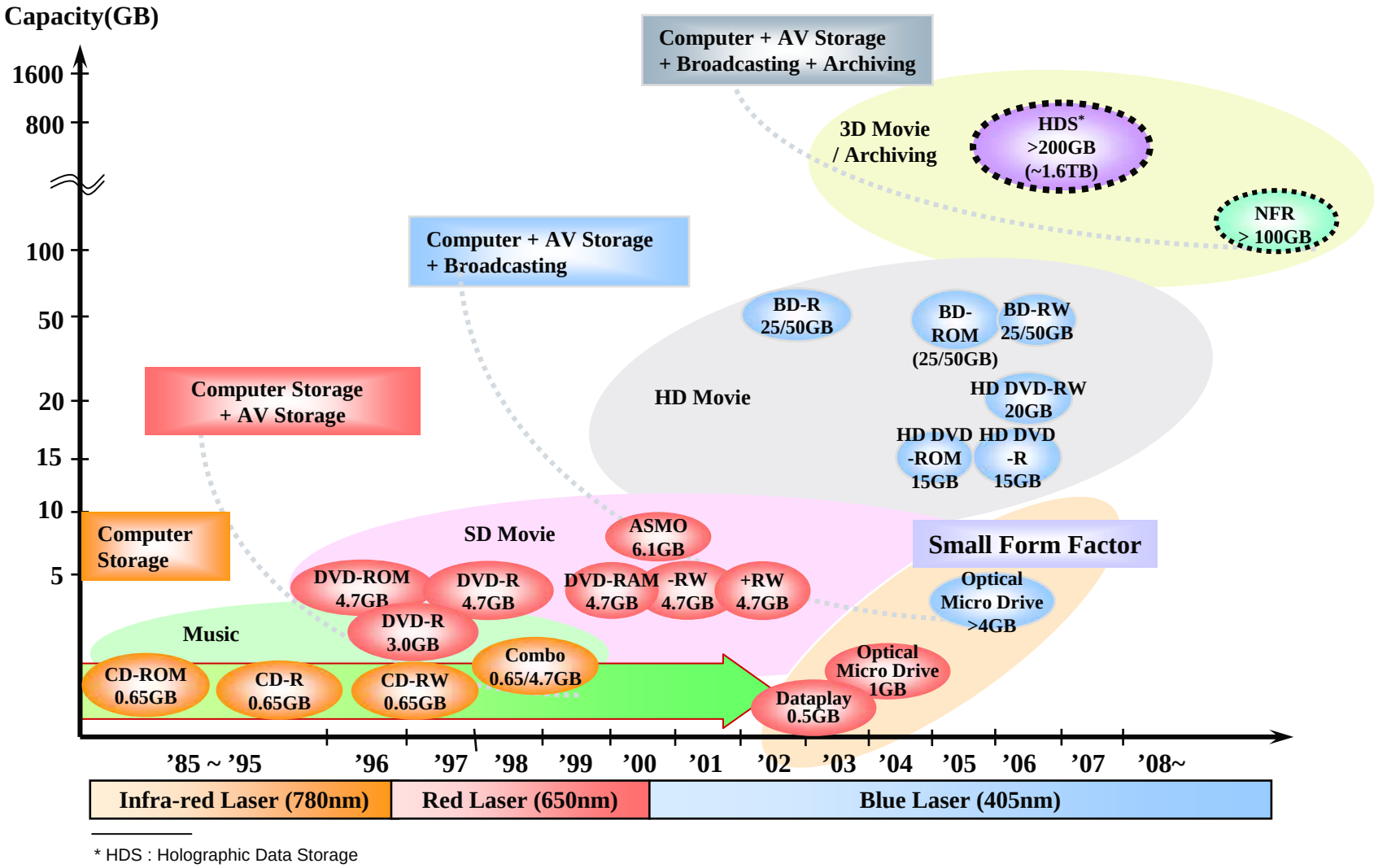


Typical 1024x1024 bit digital data

Mass Storage Technology

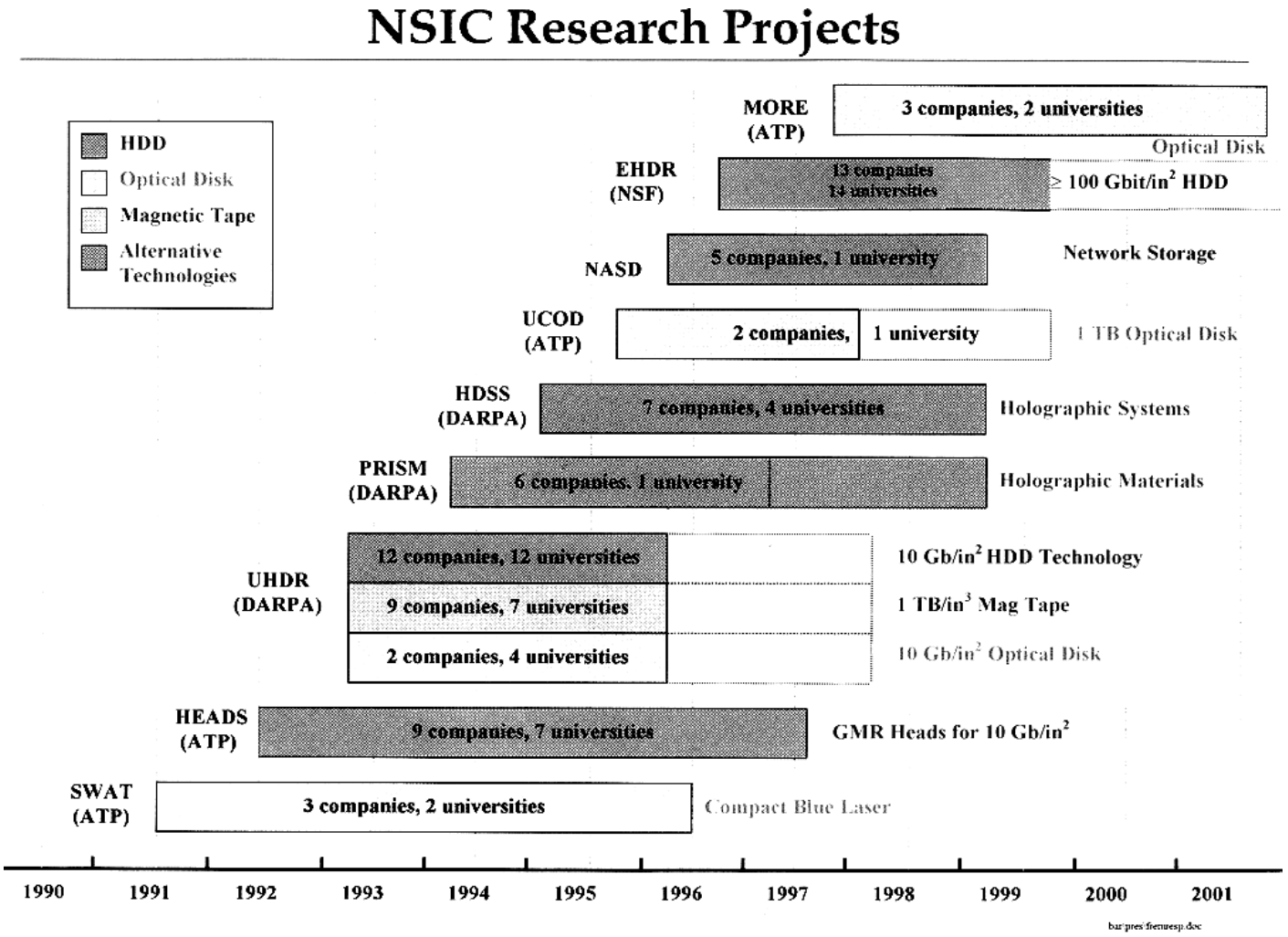


Evolution of the Optical Storage



* HDS : Holographic Data Storage

US NSIC Projects (I)



US NSIC Projects (II)

NSIC JOINT RESEARCH PROJECTS

Short Wavelength Sources for Optical Recording – 3 Companies, 2 Universities – 6/91 to 6/96 – Total $14.3M – Government Sponsor: NIST/ATP

Ultra High Density Magnetic Recording Heads – 10 Companies, 7 Universities – 8/92 to 7/97 – Total $11.8M – Government Sponsor: NIST/ATP

Ultra-high Density Recording - 19 Companies, 16 Universities – 3/93 to 9/95 – Total $22.3M – Government Sponsor: DARPA

Photorefractive Information Storage Materials - 6 Companies, 1 University, 1 Research Institute – 4/94 to 3/99 – Total $19.5M – Government Sponsor: DARPA

Holographic Data Storage Systems - 7 Companies, 4 Universities – 4/95 to 3/99 – Total $32.2M – Government Sponsor: DARPA

Ultrahigh Capacity Optical Disk - 2 Companies, 1 University – 10/95 to 12/97 – Total $13.0M – Government Sponsor: NIST/ATP

Extremely High Density Devices - 13 Companies, 14 Universities – began 11/96 – Sponsored by Companies and NSF

Network Attached Storage Devices - 4 Companies, 1 University – began 1/97 – Sponsored by Participants

Multiple Optical Recording Enhancements - 3 Companies, 2 Universities – 11/97 to 10/01 – Total $21.1M – Government Sponsor: NIST/ATP

System groups (1999)

System group	Stanford/HDSS	Stanford/HDSS	Rockwell	Lucent	NEC Research
RO or WORM or Erasable	erasable	WORM	RO	WORM	erasable
Media	LN	CROP Photopolymer	LN	Free radical PP	CdF (DX-center)
Format	90 degree crystal	165 mm disc	mult crystals	disk	bulk crystals
Capacity	100 MB	128 GB	100 MB/10 GB	50 GB/150GB	4 GB
Density	8 bit/sq. micron	55 bit/sq. micron	?	48 bit/sq. micron	100 bit/sq. micron
Access	1 msec	50 msec	50 micro sec	50 msec	
Data rate write	1 MB/sec	1 Gbit/sec	off-line	10-20 MB/sec	68 MB/sec
Data rate read	1 Gbit/sec	1 Gbit/sec	100 KB/sec	10-20 MB/sec	55 MB/sec
Access methods	spatial	rotation	AO	rotation	rotation
Wavelength	532 nm	532 nm	532 nm	532 nm	529 nm
Mux	angular	phase correlation	angular	phase correlation	angular
SLM	1 Mpix LC	1 Mpix LC	Kopin 640x480	TI DMD	fixed mask (11 & 44 Mpix)
Imaging	pixel match	pixel match	3x3 oversample	pixel match	phase conjugate
Expected outcome	demo high speed electronics	system platform complete electronics media, system tester	avionics rapid access	near on-line high density storage	currently a materials tester

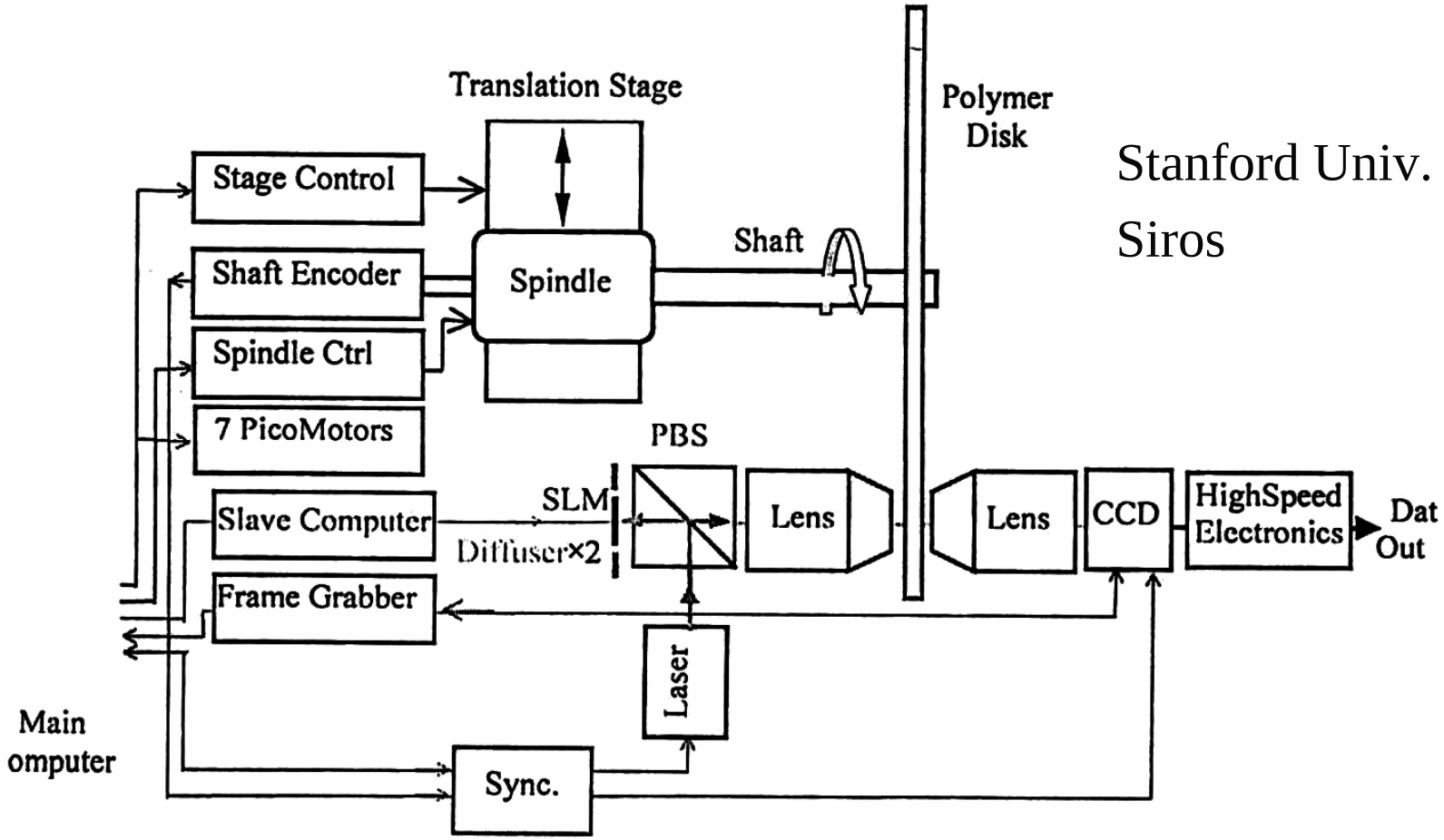
System group	StorageTek	IBM 1	IBM 2	IBM 3
RO or WORM or Erasable	erasable	WORM/Erasable	WORM	erasable
Media	LN	any	LN, 90 degrees	LN
Format	crystals on disk	coupons	coupons	coupons
Capacity	5TB			
Density	>100 bit/sq. micron	2 Gbit/sq. inch	2 Gbit/sq. inch	100 Gbit/sq. inch
Access	100 msec	10 msec	<1 msec	<1 msec
Data rate write	10 MB/sec	Mbit/sec	MB/sec	10 MB/sec
Data rate read	20MB/sec	Mbit/sec	MB/sec	10 MB/sec
Access methods	rotation, angular	angular	angular	angular
Wavelength	532 nm	variable	514 nm	532 nm
Mux	angular	angular	angular	angular
SLM	1 Mpix LC	1 Mpix	640x480 LC	1 Mpix
Imaging	pixel match	pixel match	pixel match	pixel match
Expected outcome	new functionality	teststand	mod code, ECC testing	high density demo

Table 5-1b: System Characteristics (continued)

International Workshop on HDS

NSIC

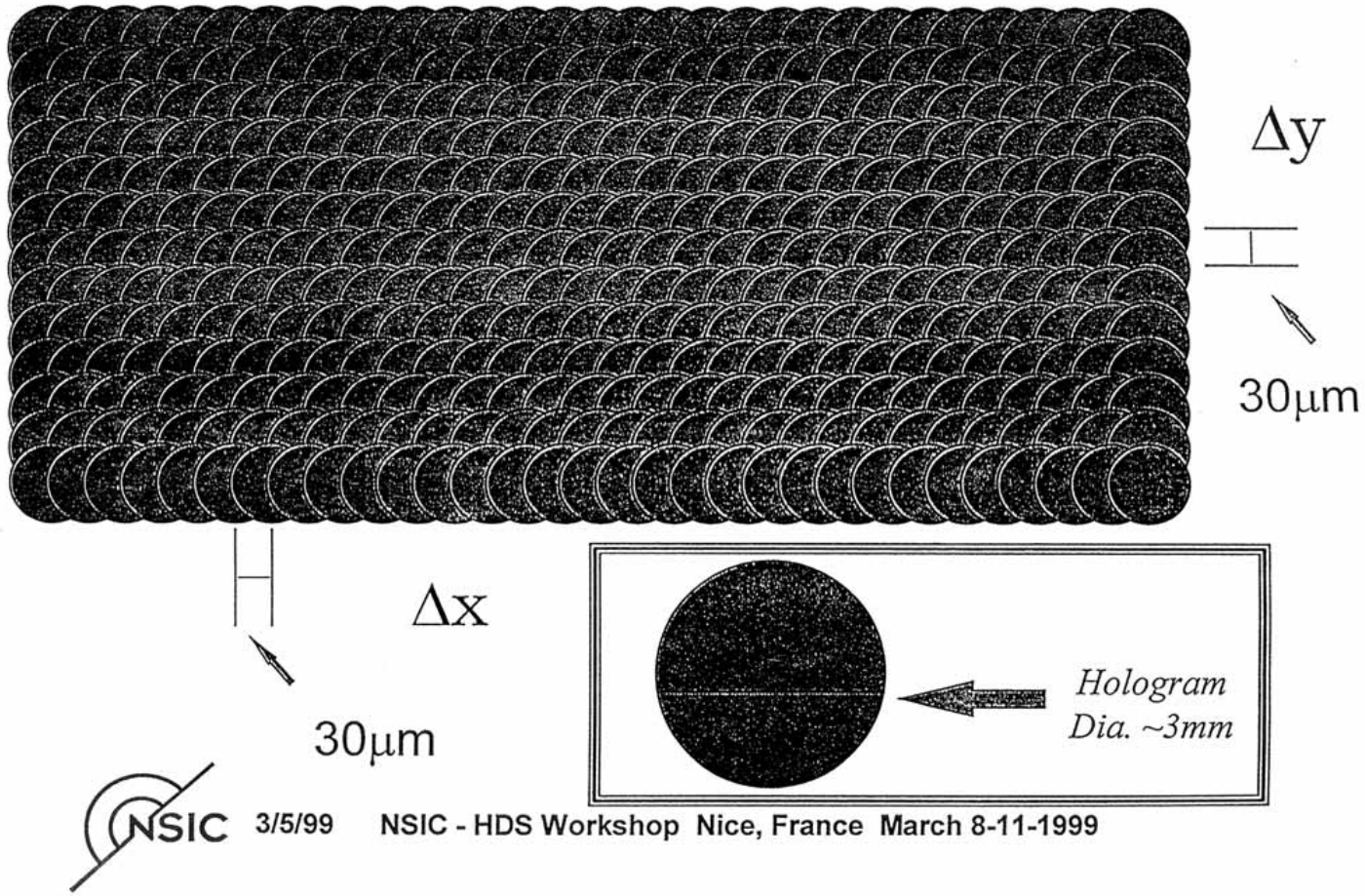
Photopolymer Rotating Disk WORM System



Stanford Univ.

Siros

System adopted random patterns - Lucent



InPhase status

Tapestry HDS 200-R

Drive
- 200 GB Capacity
- 20 MB/s or 160Mb/s Transfer Rate
- 405 nm laser
- Page-to-page seek 1ms

MEDIA
- 130 mm disc
- 50 year archive life

Core patents

1. Media:

   Stable recording medium for holographic data storage

   Novel "two-chemistry" approach for holographic media

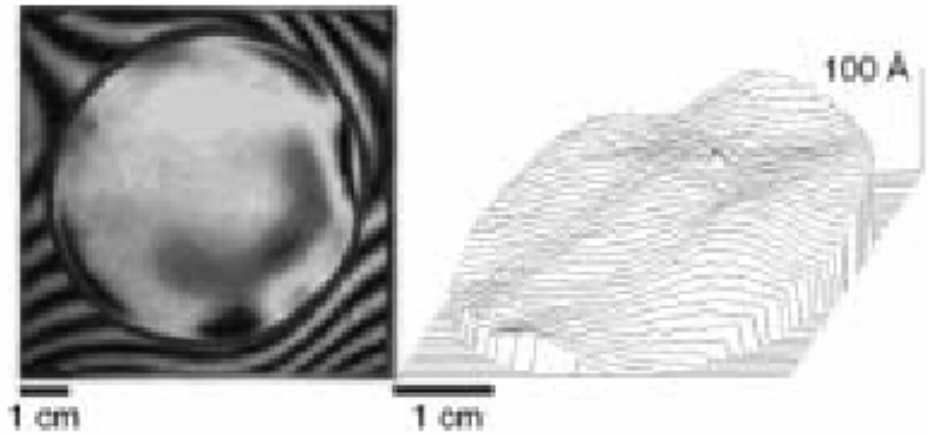
2. Multiplexing:

   Method for writing holograms in a stack

3. System:

   Application of SLM to a holographic recording process

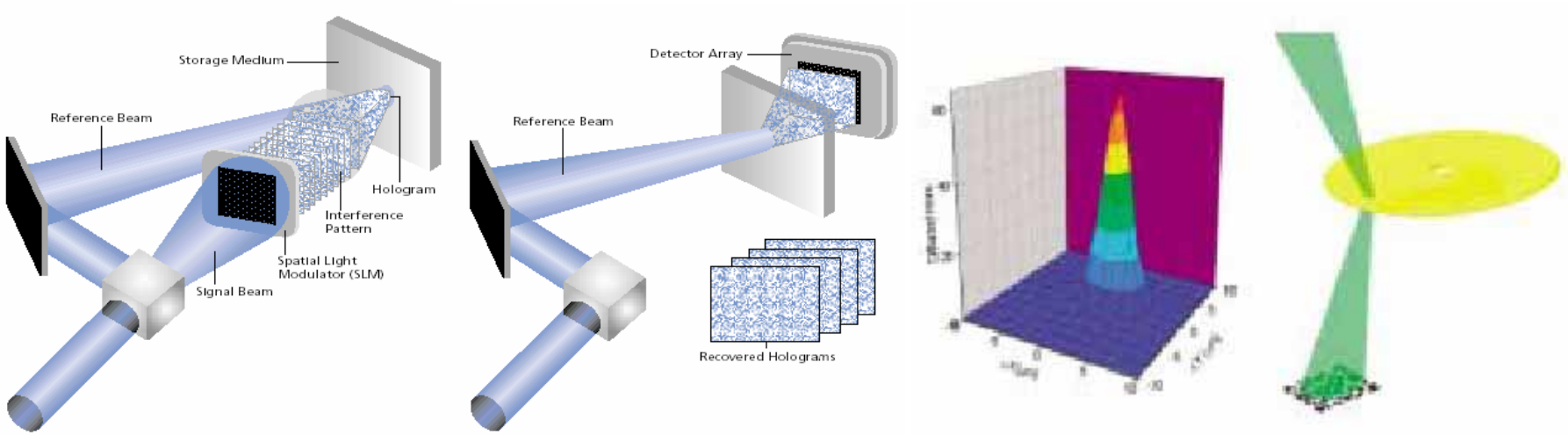
Polymer media



- *Tapestry*™ material
- *ZeroWave*™ manufacturing flat media process

- Optical quality: dimensional stability, optical flatness, low scatter
- Sensitivity: photosensitivity
- Dynamic range (M/#): millimeter thickness
- Absorption
- Volatility: heat/solvent free, non-volatile readout, long shelf-life, long archival life

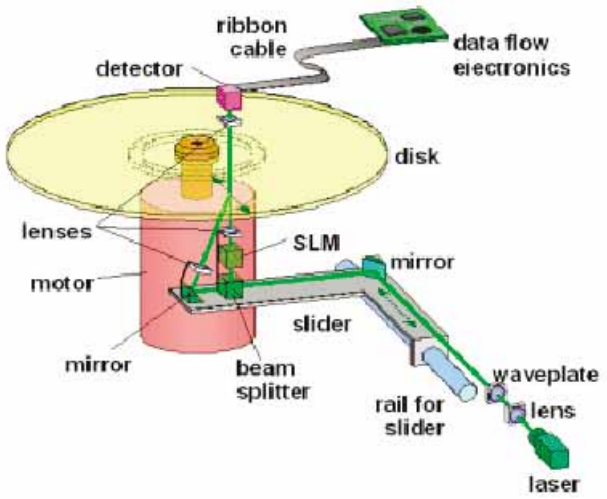
Multiplexing method



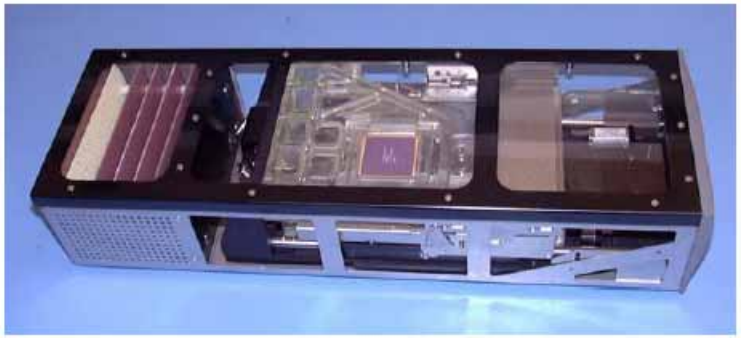
- *Correlation Multiplexing (CM)*

• Multiplexing: overlapping holograms with translations
• Reference beam: phase, amplitude, & angel difference inducing
• Single scattering phenomena: correlation

SLM recording



Example drive

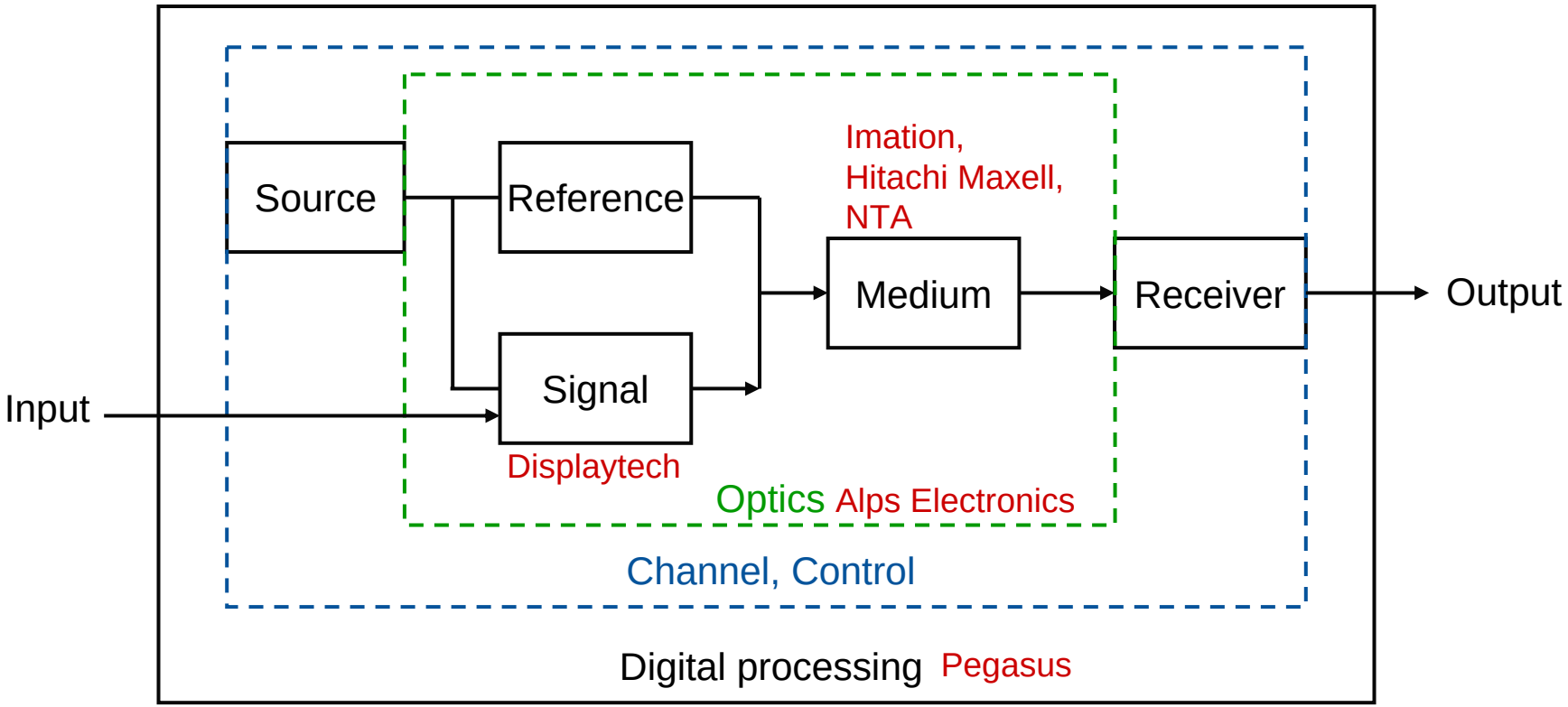


Tapestry HDS 200-R

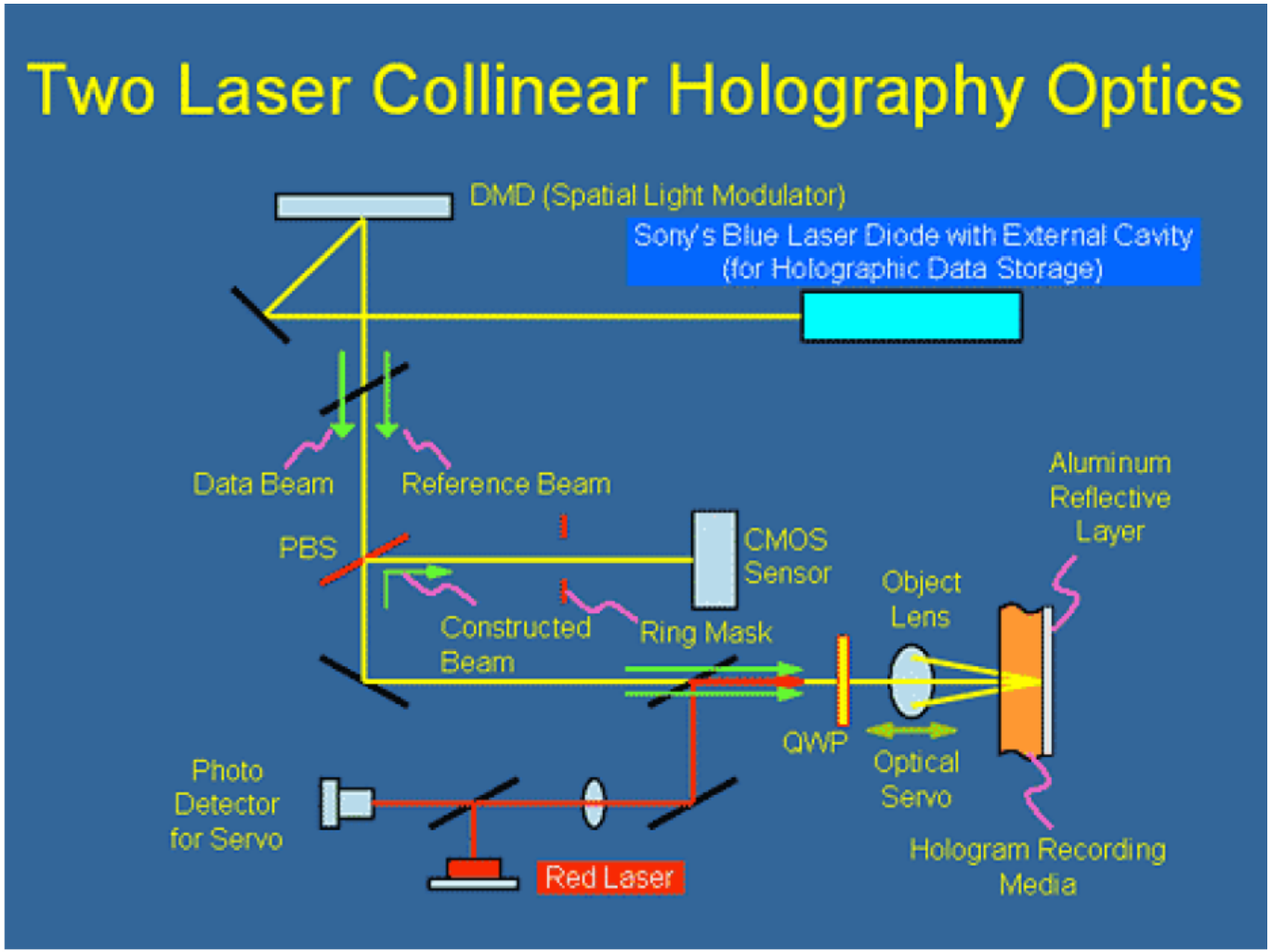
- *SLM:* Dynamic data page modulation

• *Essential & critical* for RW system

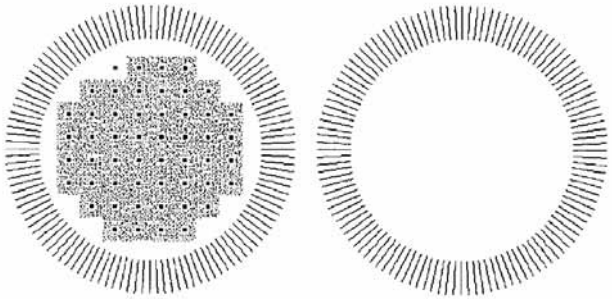
Partnerships in all areas



OPTWARE



http://www.optware.co.jp/english/what_040727.htm



(a) (b)

Fig. 2. One kind of 2-D digital page-data pattern used in the collinear holographic system: (a) write process pattern and (b) read process pattern are displayed on the SLM.

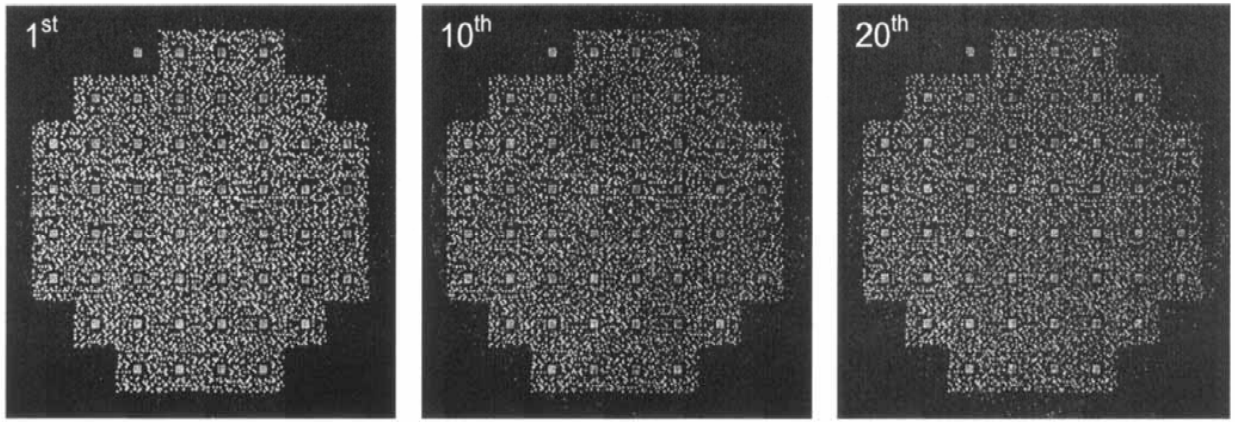
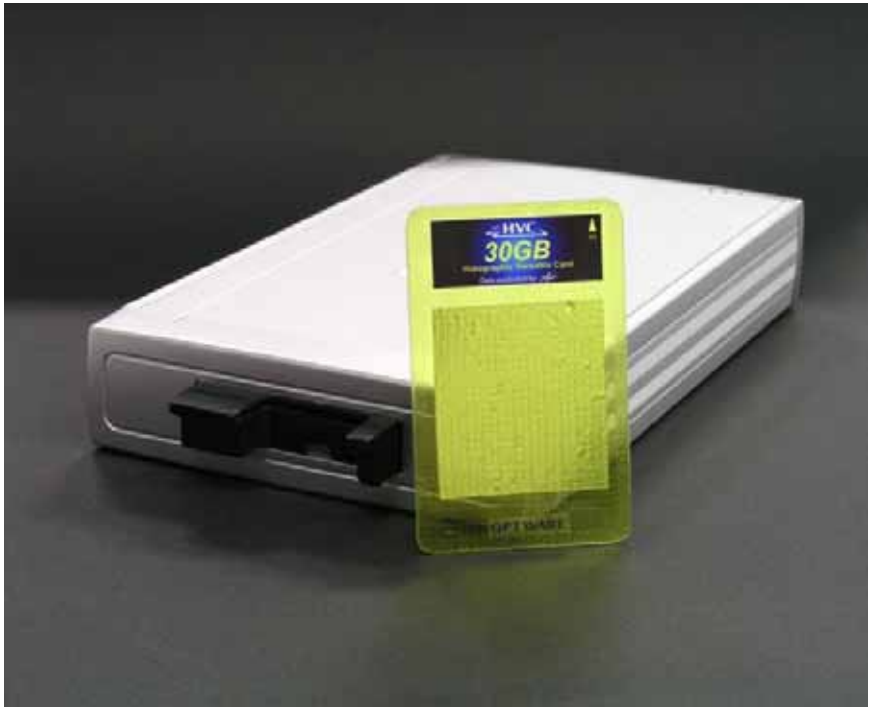


Fig. 8. Three reconstructed 2-D page-data images from the recording order of the first, tenth, and twentieth with 20 multiplex recording holograms overlapped at 3 μm.

OPTWARE



Expected price [MODULE : 200,000(JPY)]

[CARD : 100(JPY)]

CARD CAPACITY : 30GB

<JUN 08, 2005, NikkeiBP, http://techon.nikkeibp.co.jp/english/NEWS_EN/20050608/105586/>

Domestic

- **SNU (NRL HoloTech)**
  - Random pattern (RP) multiplexing
  - System development
  - Channel coding
- **Others**
  - **LG Electronics**
  - SAIT
  - Chungbuk Univ.
  - Daewoo Electronics
  - Hanyang Univ.
  - Korea Research Institute of Chemical Technology (Yonsei Univ.)
  - Kyounghee Univ.