

# Improving the storage capacity of Removable Media Storage Devices

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**Abstract-** This paper deals with an optical system that can be used for improving the storage capacity of Removable Media Storage Devices (RMSD). It is modeled based on ultrahigh density multilayer disk recording by two photon absorption techniques. Fuzzy Logic System was used to develop a controller which simulates the intelligent system for disk media production evaluation. The Fuzzy Logic has two inputs; the Numeric Aperture and the Number of Layers, while the output is Disk Storage Capacity. The System was implemented with Mat Lab simulation. An increased disk storage capacity of up wards of six terabyte was realized.

**Keywords:** disk, light, numerical aperture, optical disk, RAM

## 1. INTRODUCTION

This work "Influence of Numerical aperture Disk Media Production" is about the applications of intelligent technique in the control of a modeled disk media device that can be produced for the recording and retrieval of data.



**Fig1: Pictorial view of an Optical Disk**

A Disk is a flat shaped plate of material specifically produced to act as a medium for the storage and retrieval of information (Dan Keen, 2014). Such electronic system devices are classified as disk media. Thus disk media relates to those information storage and retrieval system devices that can be utilized in audio, video, and data applications. Prior to the advent of computer, most information storage devices were in the form of

reels that are used in film projections or telecine broadcast machines, video home sets (VHS) and audio cassettes. However, with the emergence of personnel computer, there has been a significant change in the requirements for removable media storage system devices (RMSDs). The first ever removable media storage device is the magnetic floppy disk. Others include the solid state Flash drive and the Hard disk drive.



(a) Floppy disk  
(c) Hard disk drive

(b) Flash drive

**Fig 2: Some Removable Media Storage Devices** (Keen 2014).

Subsequent developments in the RMSD are informed by improved storage and retrieval parameters including capacity, speed, access time, data transfer rate, data availability, backward compatibility, durability and convenience. Consequently the compact disk (CD) was introduced. The CD has a maximum storage capacity of 793 megabytes. The digital versatile disk (DVD) followed with an improved storage capacity of 15.9 Giga bytes. Presently, the fluorescence multilayer disk (FMD) or the constellation three dimensional disk (C3D) are being developed. It has a capacity of one Tetra bytes.

The technology applicable in the read and write data on RMSD includes; magnetic format that uses magnetic particles and magnetic fields, optical formats that uses laser light and optical sensors, magnetic optical and magneto-optical hybrid that uses a combination of magnetic and optical properties to increase storage capacities, holographic format that can write and read one million bits of data in a single flash of light. Figure 3 shows the traditional classification of data storage devices.

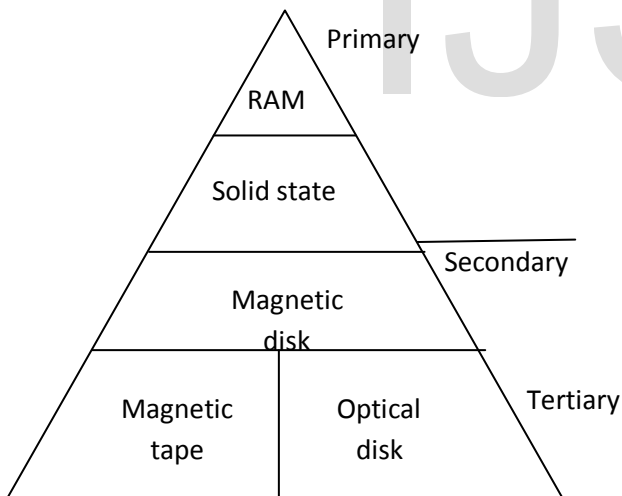


Fig.3: Storage hierarchy showing the traditional classification of devices for data storage

At the top of the hierarchy is the primary storage. Belonging to this classification is the Random Access Memory (RAM) used for caches and main memory. Typical RAM technologies are Static RAM and Dynamic RAM. Below RAM is Solid State memory and Magnetic disk. They are

commonly called Secondary Storage devices. Typical devices in this category are the Floppy disk, Flash drives and Hard disk drives. At the bottom of the hierarchy are tertiary storage devices. These groups include magnetic tapes, Optical tapes, Optical disk and Holographic storage technologies.

The technology of RMSD is still evolving. With the rapid advancement of internet and computer technology, the demand of massive and inexpensive data storage tools has increased dramatically. For the last twenty years, optical disks, in particular read-only compact disks (CDs) and digital versatile disks (DVDs) have enabled us to replicate massive amount of data in an inexpensive removable format. Optical disks are also popular as recording devices in the formats of compact-disc-recordable (CD-R) and compact-disc-rewritable (CD-RW). Other formats, such as DVD-R and DVD-RW, are just emerging into the market of massive data storage. As the optical data storage technology evolves, the capacity of an optical disk increases (Tieke et al. 1999). The CD and DVD devices use the mechanism of far-field single-layer recording. A more advanced technology, which uses multiple layers on a single disk, is called volumetric bit-wise optical data storage. This new technology is expected to extend the capacity of optical disks in the orders of magnitude beyond what is found in CD and DVD (Ahmed et al, 2007).

This paper presents the characterization of optical systems that can be used for volumetric bit-wise optical data storage. One promising direction to satisfy these requirements with low cost systems is the use of optical volumetric multi-layer disk media. The application of intelligent technique in disk media production can go a long way in improving the quality of removable media storage devices (RMSDs) in areas of storage capacity, data transfer rate, access speed, access time, data availability, backward compatibility and durability.

## 2. THEORY

### Optical Disc Technology.

In optical recording, a non-contact optical head uses a laser beam to store information on a disc surface by creating pits in the surface material.

LASER which stands for Light Amplification by the Stimulated Emission of Radiation is monochromatic, directional, coherent and collimate. It is characterized with one wavelength. It is emitted as a relatively narrow beam in a specific direction. The light from a laser is in phase both in time and space. Laser operates within the infrared, visible and ultraviolet bandwidth of the electromagnetic spectrum, corresponding to a wavelength range of 100 nanometer to 1 Pico meter.

The radiation energy of laser is given by  $E=MV^2$  and is inversely proportional to wavelength; where E is Radiation Energy, M is the mass of the laser and V is the velocity of Laser propagation. Laser light consists of photons, each with discrete quantum of energy proportional to their wavelength. For an electron to be freed from a surface it would need a photon with enough energy to overcome the energy that bound it to the atom. Making light brighter or reducing the wavelength would supply more photons. Light with a shorter wavelength consisted of higher energy photons that could supply the needed energy to free electron. The portion of the electromagnetic spectrum where lasers operate are infrared, visible, and ultraviolet radiation (Parthenopoulos et al,1989). Table1 shows the wavelength of Laser Radiations.

**Table 1:** Wavelength classification of Laser Radiations.

Near Infrared	750 nm - 3000 nm
Far Infrared	3000 nm - 1 mm

The energy produced by laser at its incidence object is greater at lower wavelength. The physical size of a laser beam depends on the material used for light emission, the output power and the pulse duration of the beam. Lasers use two layers of semiconductor substances such as gallium arsenide. Optical discs are called write once, read many (WORM) device. The beam width is the single most important characteristic of a laser beam profile. At least five definitions of beam width are in common use:  $D4\sigma$ , 10/90 or 20/80 knife-edge,  $1/e^2$ , FWHM, and D86. The  $D4\sigma$  beam width is the ISO standard definition and the measurement of the  $M^2$  beam quality parameter requires the measurement of the  $D4\sigma$  widths.

The other definitions provide complementary information to the  $D4\sigma$  and are used in different circumstances. The choice of definition can have a large effect on the beam width number obtained, and it is important to use the correct method for any given application. The  $D4\sigma$  and knife-edge widths are sensitive to background noise on the detector, while the  $1/e^2$  and FWHM widths are not (S. Ravi, 2013)). The fraction of total beam power encompassed by the beam width depends on which definition is used. The  $M^2$  parameter is a measure of beam quality; a low  $M^2$  value indicates good beam quality and ability to be focused to a tight spot. The surface of a cross section of an optical disk track on which laser modulated signal is incident on is as shown in fig 4.

Name	Wavelength
Ultraviolet	100 nm - 400 nm
Visible	400 nm - 750 nm

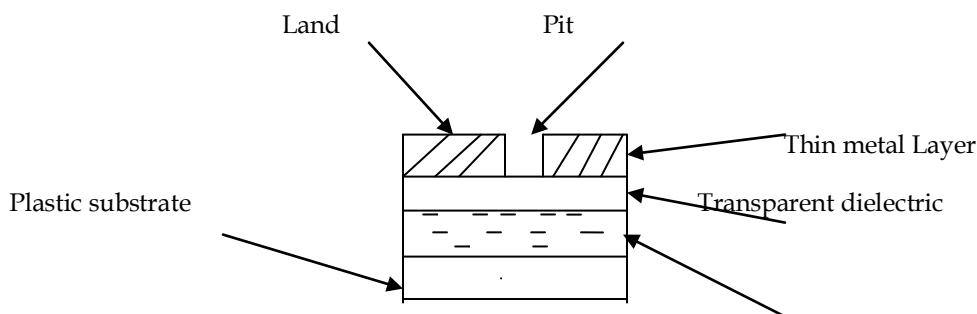


Fig.4: Structural diagram of an optical disk.

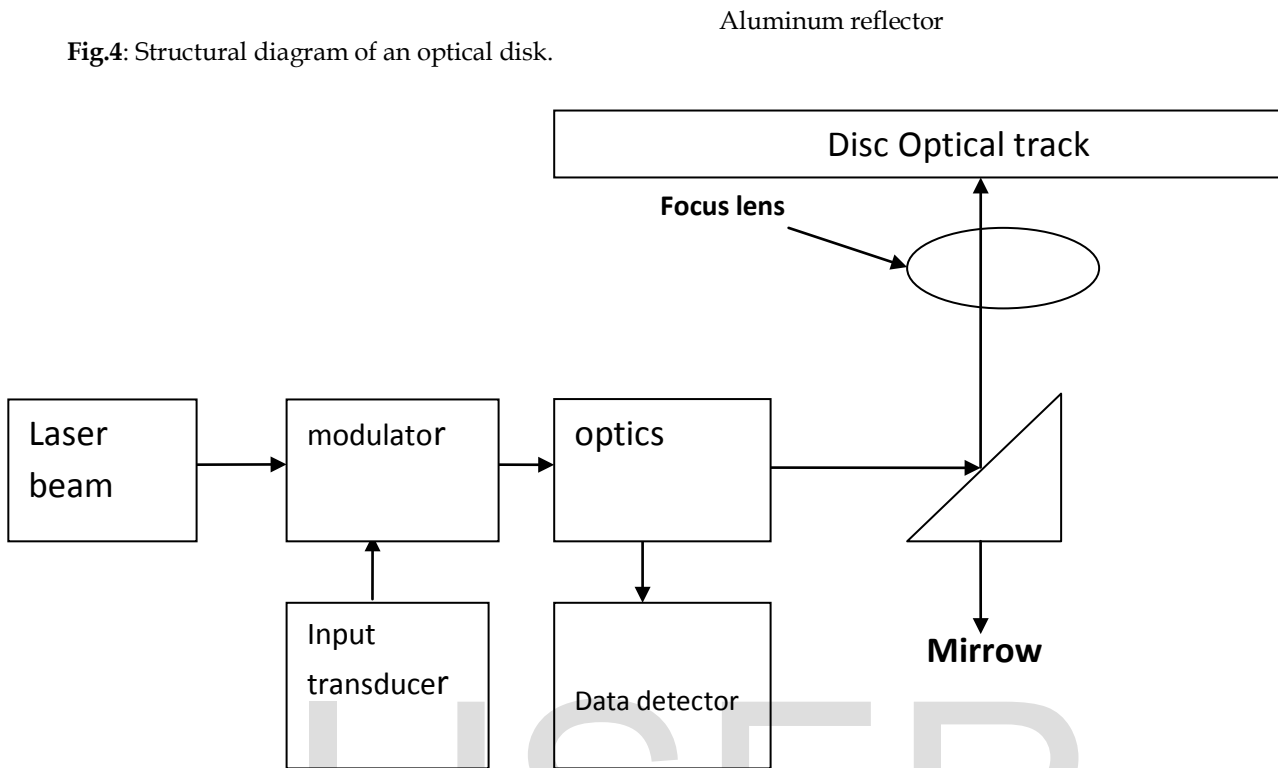


Fig. 5: Block diagram of optical disc technology (Chervenak 1994).

The Fig.5 illustrates in a block form, how data is recorded or retrieved from disk track. Figs.4 and 5. are used to illustrate optical disc technology. During writing, in response to an electrical input signal, a highly focused laser beam melts a small region of the metal layer opening a hole or pit. Data are thus encoded and stored as alternating regions of pits and lands. The encoded binary data (bits) in the form of pits (binary value of 0 or off, due to lack of reflection when read) and lands (binary value of 1 or on, due to a reflection when read) on a special material (often aluminum) on one of its flat surfaces. The encoding material sits atop a thicker substrate (usually polycarbonate) which makes up the bulk of the disc and forms a dust defocusing layer. The encoding pattern follows a continuous, spiral path covering the entire disc surface and extending from the innermost track to the outermost track.

The data is stored on the disc with a laser or stamping machine, and can be accessed when the data path is illuminated with a laser diode in an optical disc drive which spins the disc at speeds of about 200 to 4,000 RPM or more, depending on the drive type, disc format, and the distance of the

read head from the center of the disc (inner tracks are read at a higher disc speed). The pits or bumps distort the reflected laser light, hence most optical discs characteristically have an iridescent appearance created by the grooves of the reflective layer. During reading, a lower intensity, unmodulated laser beam is reflected off the surface of the disc. A photo detector interprets information stored on the disc by detecting differences in reflectivity between pits and holes on the thin metal layer. The encoding may be likened to a pit representing a zero and a land representing a one. On an optical disc, data may be stored in a single track or as a series of concentric circular tracks. The system works with three servo mechanisms; one for tracking, second for focusing the laser beam, and the third for controlling the speed of rotation of the disc to ensure that the data transfer rate is constant.

Holographic storage technology.

A hologram is a block or sheet of photosensitive material which records the interference of two light sources. To create a hologram, laser light is first split into two beams, a source beam and a reference beam. The source beam is then

manipulated and sent into the photosensitive material. Once inside this material, it intersects the reference beam and the resulting interference of laser light is recorded on the photosensitive material, resulting in a hologram. Once a hologram is recorded, it can be viewed with only the reference beam. The reference beam is projected into the hologram at the exact angle it was projected during recording. When this light hits the recorded diffraction pattern, the source beam is regenerated out of the refracted light. An exact copy of the source beam is sent out of the hologram and can be read by optical sensors (Heanue, 1994)). Precise laser equipment is used at the factory to create the hologram. A recording material which can recreate recorded images out of natural light is used, and not a high-tech equipment to view the information stored in the hologram.

Holographic Data Storage has advantages over conventional storage methods in the following areas;

Data is stored in all three dimensions of the material and not just the surface, read/write speeds are also much higher since data is written and read out as 2D digital or analogue images in a 3D volume rather than a bit stream and the bit rate error is also decreased considerably because error causing factors such as scratches, dust, etc tend to affect the surface only and since a hologram is

recorded as a complex interference pattern in the bulk of the material, these affects are limited.

(i) Holographic images

Holographic images interfaces empower operators to enter commands and data into a wide range of electronic equipment by simply passing a finger through holographic images of what would otherwise be the keys of a keypad or keyboard, appearing to float in the air at a convenient location in front of the equipment. An infrared sensor scans the plane of those images to detect the intrusion of a finger into the desired portion of those images, identifies which number or symbol has been selected and transmits that selection to the equipment's internal software, much the same way pressing a button on any ordinary keypad would.

Holographic images solve many problems posed by conventional, tactile keypads and keyboards, particularly those regularly subjected to contaminants, customer abuse, dirt, moisture, temperature fluctuations and shock.

Like an optical technology, it works with three servo drive mechanism; one for tracking or layer selection, the second for actuating the lens system and the third for controlling the spindle of the disc which spins between 200 and 4000 rpm. Figs.6 and 7 illustrates the holographic technology.

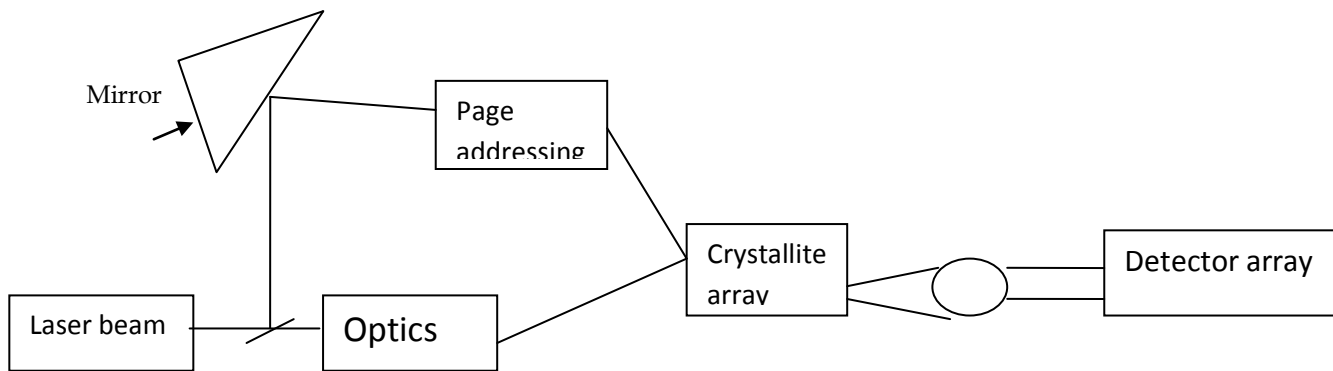


Fig.6: Block diagram of the holographic disc technology (Chervenak 1994).

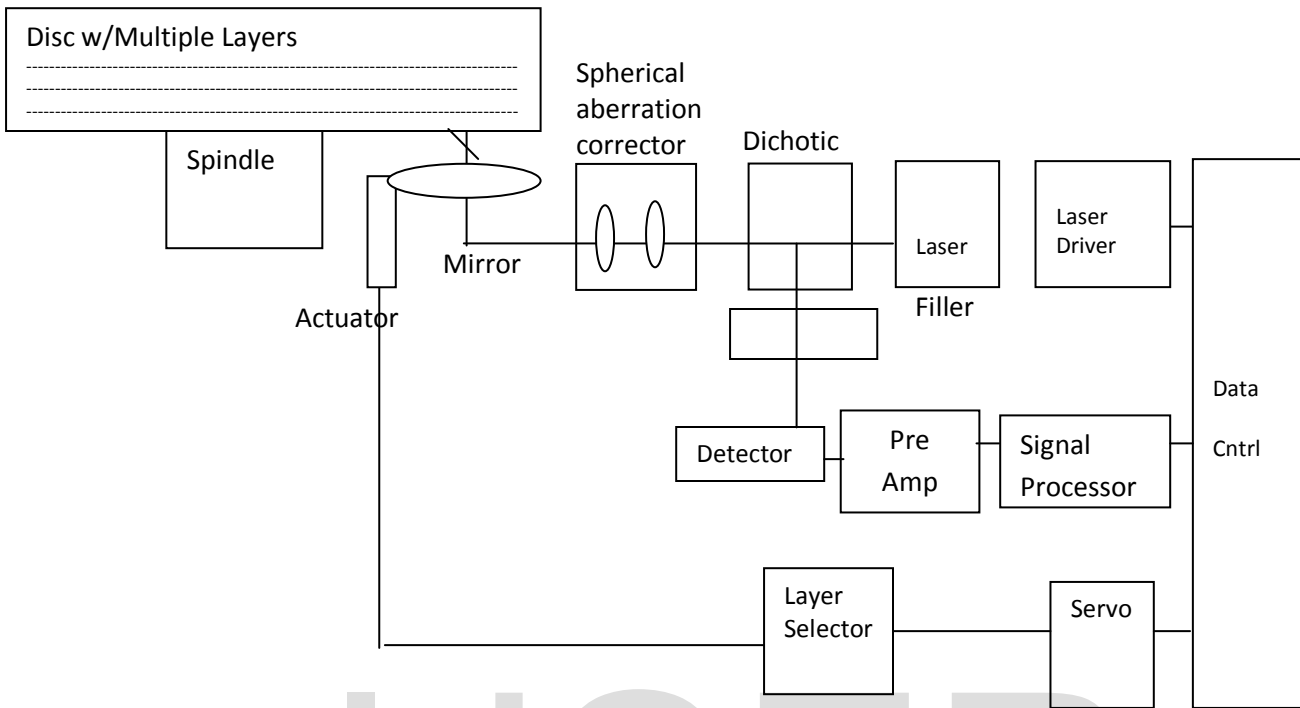


Fig.7: Block diagram of the holographic drive

Solid Immersion Lens (SIL), Volumetric Storage Optics and Volumetric Storage Media  
The solid immersion lens (SIL) is currently being developed as a near-field data storage technique (Mizuno et al. 2001), which utilizes evanescent energy to greatly increase NA and produce extremely small optical spots. A typical arrangement for the SIL system is shown in Fig. 2.7. A SIL, which is an image-centric hemispherical lens with high refractive index, is placed in near

contact with the recording medium. Light from a laser passes through the beam splitter and is focused near the bottom of the SIL by an objective lens. The size of the light spot is smaller than the laser wavelength. The evanescent field generated from the bottom of the SIL is coupled into the recording medium, which leads to a small data mark. Hence, the data capacity is greatly increased on each layer.

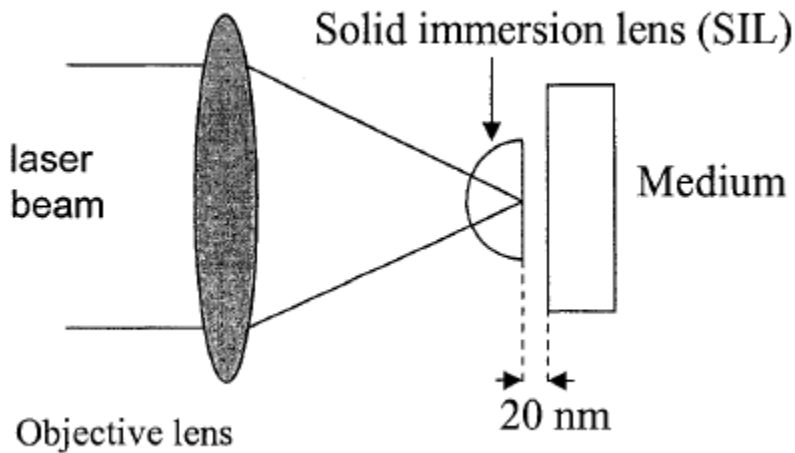


Fig.8: Typical near-field system using SIL (Mizuno et al. 2001).

A second way to increase the data capacity is to use volumetric optical data storage technology. Currently, volumetric technology is divided into two research areas, which are holographic optical data storage and volumetric bit-wise optical data storage. Since the invention of holography (Gabor 1948), people have tried tirelessly to develop optical memory based on the holographic optical interference technique. Chen et al (1968) first proposed to use LiNbOS as the holographic storage medium. In holographic storage, data sets are transferred to and from storage material as 2-D images composed of thousands of pixels, with each pixel representing a single bit of information. However, no one location in the medium is responsible for storing that one bit; each bit is distributed throughout the recorded interference fringes.

#### Bit-Wise Volumetric Optical Data Storage

There are three categories of material that have been used in bit-wise volumetric optical data storage technology. The first category is refractive-index-change material, which consists of photopolymer, photorefractive, and photo chromic material. The second category is fluorescent material. The third category is material with Super-Rens structure.

### 3. METHODOLOGY

Development of a model for optical data storage capacity.

The ultrahigh density multi-layer disk recording by two photon absorption Model is assumed. In this model, a high Numerical Aperture (NA) objective lens ( $NA > 1$ ) with a long working distance ( $> 100\text{mm}$ ) together with a multilayer volumetric optical media provides an important direction towards the realization of ultra high density multi-layer recording by two-photon absorption. A high NA objective lens decreases bit size, increases the volumetric density, and reduces the recording laser power requirements for a given recording speed.

For Increasing Disk Capacity, the parameters required for a 2-photon 3-D optical data storage disk, are:

- (i) The disk.

The Disc is circular in shape. The surface area of a circular disk is  $\pi r^2$ ; where  $r$  is the radius. In a disk media, there is a limited portion in which data can be recorded for retrieval. This boundary is defined by the difference between the maximum recording surface area and the minimum recording surface area.

The maximum recording surface area,

$$A_{\max} = \pi r_{\max}^2 \tag{1}$$

The minimum recording surface area,

$$A_{\min} = \pi r_{\min}^2 \tag{2}$$

The portion of the disk on which data can be stored

$$S = A_{\max} - A_{\min} \text{ or}$$

$$S = \pi r_{\max}^2 - \pi r_{\min}^2 \text{ or } S = \pi(r_{\max}^2 - r_{\min}^2) \quad (3)$$

Where "r" is the radius of the circle.

(ii) The optical system.

The area raw capacity of the disk is proportional to the size of Numerical aperture (NA), and inversely proportional to the bit size defined by  $l_{\text{pit}} \times w_{\text{pitch}}$  in the X-Y plane.

The total area of raw capacity is expressed as:

$$C_{\text{areal}} = \frac{\pi(r_{\max}^2 - r_{\min}^2)}{l_{\text{bit}} \times w_{\text{pitch}}} NA \quad (4)$$

$r$  in equation 3 is equal to the beam radius of the laser ( $W_o$ )

$$W_o = \text{radius of disk } (r) \text{ times wavelength} = 0.61\lambda \quad (5)$$

Also, the bit size of a laser modulated data defined

$$\text{by } l_{\text{pit}} \times W_{\text{pitch}} \text{ is equal to beam quality parameter } (M^2 \geq 1) \text{ times wave length} = 1.22\lambda \quad (6)$$

By substituting equations 5 and 6 in equation 4,

$$C_{\text{areal}} = \pi(0.61\lambda)^2 NA / 1.22\lambda \quad (7)$$

The volume raw capacity of a 2-photon 3-D optical data storage disk

$$\text{is: } C_{\text{total}} = C_{\text{areal}} * N_{\text{layer}} \quad (8)$$

$$N_{\text{layer}} = T_{\text{disk}} / S_{\text{layer}} \text{ is the number of layers.}$$

$T_{\text{disk}}$  is the thickness of the disc;

$S_{\text{layer}}$  is the layer separation.

Generally,  $T_{\text{disk}}$  should be smaller than the working distance of the objective lens. Substituting 7 into 8, the storage capacity

$$C_{\text{total}} = \left[ \pi (0.61\lambda)^2 NA / 1.22\lambda \right] N_{\text{layer}} \quad (9)$$

For Ultra high density multi-layer disk readout; During readout, fluorescence is emitted in  $4\pi$  radians. The objective lens collects only a small portion of the fluorescence. The substrate of the disk is  $n_1 = 1.492$ . The critical angle affects the maximum solid angle that can be collected. Total collection efficiency is the ratio of the collected solid angle to  $4\pi$  radians:

$$n_{\text{collection}} = (1 - \sqrt{1 - (\frac{NA}{n_1})^2}) / 2 \quad (10)$$

$$NA = n_1 \sin \theta \text{ lens.}$$

$n$  = refractive index in image space.  $\Theta$  = marginal ray angle in image space.

Application of Fussy system on optical data storage capacity.

For the intelligent system for disc media production controller design, there are two inputs and one output that are designed through the toolbox. The inputs are numerical aperture and number of disc layers. The output is the disc capacity.

#### 4. DATA PRESENTATION AND ANALYSIS

Comparison of disk media devices.

Table 2 below shows the evaluation of some parameters of removable media storage devices.



Table 2: Evaluation of removable media storage devices.

s/n	Name of disk media	Size	Read and write principle	Maximum storage capacity	Others
1.	Floppy disk	8', 5', 3.5'	Magnetic	1.44megabyte	Low speed, not durable
2.	Hard disk drive		Solid state	40 megabyte	No rotation
3.	Flash drive	2'	Same	8 gigabyte	Convenience, no rotation
4.	Compact disk	120mm diameter,1.2mm thickness	Optical	7.93 megabyte	Speed, durability, convenience
5.	Digital versatile disk	Same	Same	15.9 megabyte	Same
6.	Fluorescent multilayer disk	Same	Same	1 terabyte	Same

Table 3: The percentage storage capacity of RMSD

S/N	RMSD	Maximum storage capacity	Percentage storage capacity
1	Floppy disk	1.44 MB	0.0001 %

2	Hard disk drive	40 MB	0.0039 %
3	Flash drive	8 GB	0.7813 %
4	Compact disk	7.9 MB	0.0008 %
5	Digital versatile disk	15.9 GB	1.5528 %
6	Fluorescent multilayer disk	1 TB	97.66 %
Total		1.02394937 TB	99.9998 %

Demonstration of the model on optical data storage by simulation.

Equations 7 or 9 and 10 of the model were used in MATLAB simulation. Below are the model parameters for the 2-photon 3-D optical data storage disk.

Radius of beam width  $r = 0.61\lambda/NA$

Wavelength ( $\lambda$ ) = 460nm

Numerical aperture (NA) = 0.2 to 1.8.

Pulse repetition rate = 76MHz

Pulse width = 200 per second

Bit length per bit =  $1.22 \lambda/NA$

Bit size = 1 bit x w pitch =  $1.22 \times \lambda$

$r = (r_{2max} - r_{2min})$

$\pi = 22/7$

$n_1 = 1.492$

No of Layers = 10

For equation 9, the simulated data from the numerical aperture used is as shown in table 4.

Table 4: Variation of Storage Capacity with increasing NA.

numerical aperture (NA)	Area (surface) Capacity: TB
0.2	0.8819
0.4	1.7638
0.6	2.6457
0.8	3.5275
1.0	4.4094
1.2	5.2913
1.4	6.1732
1.6	7.0571
1.8	7.9370

For equation 10, the simulated data from each of the numerical aperture used for collection

efficiency is also shown in table 5. It is evident from that table that the maximum efficiency occupant is at the numerical aperture of 1.4. Beyond that point the collection efficiency becomes complex. It is therefore at this point where numerical aperture is 1.4 that puts a limit to the achievable storage capacity of 6.1732TB.

Table 5: Variation of Collection Efficiency with increasing NA.

numerical aperture (NA)	collection efficiency
0.2	0.0451
0.4	0.1830
0.6	0.4221
0.8	0.7795
1.0	1.2893
1.2	2.0288
1.4	3.2714
1.6	5.0000 - 1.9366i
1.8	5.0000 - 3.3745i

## 5. ANALYSIS

Effect of Numeric Aperture on storage capacity.

Using table 4, the graph of area capacity (storage capacity) versus Numerical aperture was plotted as shown in fig below

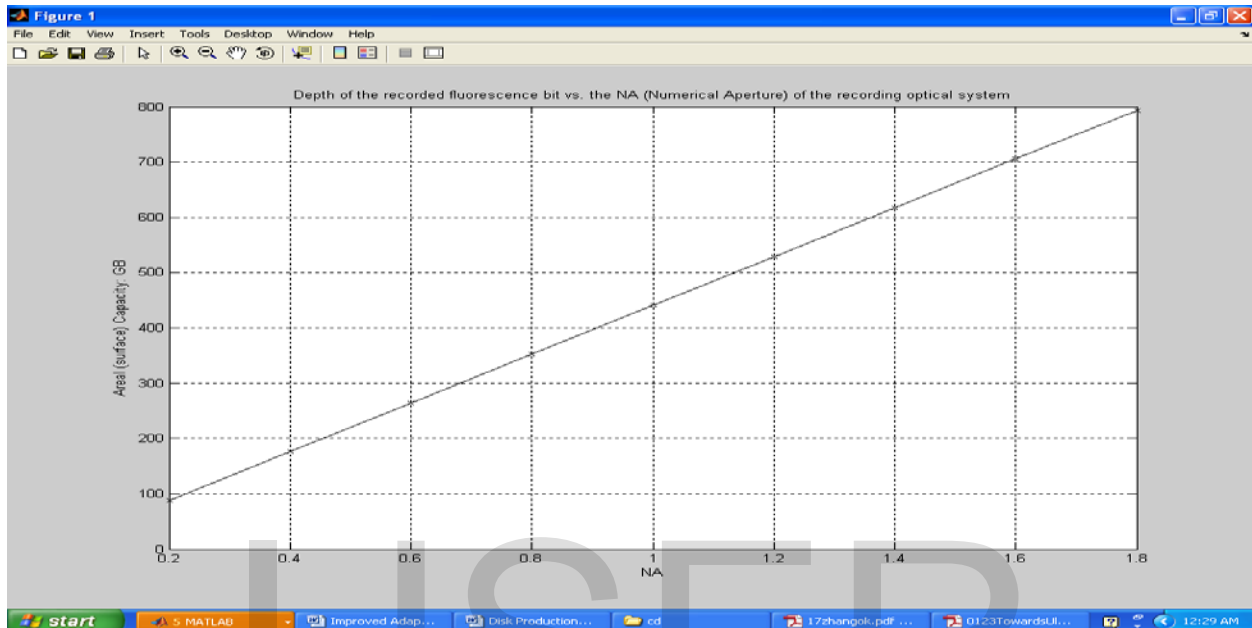


Fig.15: Storage Capacity and NA plot for disk

It can be seen clearly that as Numerical aperture increases the storage (surface) capacity of the Disc increases. In order to increase the volumetric capacity (areal density, and volumetric density) a tradeoff between high NA and lens working distance is considered, as well as recording laser power requirements that are now examined.

## 6. CONCLUSION

Influence of the numerical aperture on a 3-D multi-layer optical data storage system is analyzed based on simulation results. With a Numeric Aperture of 0.2 up to 1.4, there is remarkable increase in storage capacity. Further increase in Numeric Aperture leads to further increase in the storage capacity. However, the collection efficiency increase is synonymous with increase in storage capacity up to a Numeric Aperture of 1.4. Beyond this value of Numeric Aperture, the collection efficiency becomes complex. This provides a limit to the possible storage capacity realizable with Fluorescent Multilayer Disk. There is not yet an established factor that can limit the storage capacity with increase in the number of disk layer except perhaps the penetration ability of the laser beam. A high NA objective lens decreases bit size,

layer separation, and increases the volumetric capacity.

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