PETABYTE MASS MEMORY SYSTEM USING THE NEWELL OPTICEL*

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Abstract

A random access system is proposed for digital storage and retrieval of up to a Petabyte of user data. The system is comprised of stacked memory modules using laser heads writing to an optical medium, in a new shirt-pocket-sized optical storage device called the Opticel*. The Opticel described is a completely sealed "black box" in which an optical medium is accelerated and driven at very high rates to accommodate the desired transfer rates, yet in such a manner that wear is virtually eliminated. It essentially emulates a disk, but with storage area up to several orders of magnitude higher.

Access time to the first bit can range from a few milliseconds to a fraction of a second, with time to the last bit within a fraction of a second to a few seconds. The actual times are dependent on the capacity of each Opticel, which ranges from 36 Gigabytes to 6.75 Terabytes. Data transfer rate is limited strictly by the head and electronics, and is 15 Megabits per second in the first version.

Independent parallel write/read access to each Opticel is provided using dedicated drives and heads. A Petabyte based on the present Opticel and drive design would occupy 120 cubic feet on a footprint of 45 square feet; with further development, it could occupy as little as 9 cubic feet.

Introduction

The Compact Disc digital audio player dramatically illustrated the classic criteria for a successful new market entry: it produced a significantly higher-quality product in a smaller size, with important new features yet at a competitive price, in a marketplace which had stagnated.

The Newell Opticel promises the equivalent for video bandwidths: a digital recorder-player module which, by meeting the same criteria, would bring about an even more far-reaching revolution in the computer and home-entertainment markets.

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* Trademark

The Opticel drive combines novel cartridge concepts with three other discrete components: optical heads, optical media, and signal and control electronics. It is packaged in a standard 3-1/2-inch form factor, one-half the volume of the highest density 5-1/4-inch CD ROM drive, with over ten times its capacity, yet with access times comparable to single-disk systems, and transfer rates limited only by the digital electronics.

There are many development efforts under way seeking such an objective. Those known all suffer critical shortcomings: disk-based systems are bulky and have limited transfer rates; tape-based systems have poor access times. The Opticel retains the advantages of both with none of the fundamental disadvantages.

The Optical Head

Primelink is developing two heads:

(a) An IR-laser head, on a conventional 2-axis fine actuator movement (tracking and focus) and a stepper-motor/ball-screw carriage assembly for coarse tracking, is being designed.

(b) A red-laser-based, integrated, solid-state, multi-channel head system is being researched, with no tracking movements (i.e. no moving parts).

The first head will go to production in mid-1995; the second is scheduled for release in a second-generation product (probably around the year 2000).

The Optical Recording Media

Primelink has working agreements with two U.S. companies for archival or WORM optical tape, and for non-archival, erasable tape. Both are compatible with the optical head lasers.

The Data Encoding/Decoding Method

Background - The encode/decode technique normally used in today's WORM disks is to ablate a pit using an IR laser. The data are encoded by phase-modulating the position of the pit-edge along the track.

If the wavelength of the laser is λ, the numerical aperture of the lens N, and ablation is set to occur at the 50% level on the Gaussian energy curve, then the pit diameter becomes

$$d_{pit} = \frac{\lambda}{2N} \tag{1}$$

A commercially available head[1] employs, for example, λ = 785 nm, NA = .53. This gives a spot size of 0.74 micron. To allow for inter-track grooves and tracking servo error, a track pitch of 1.6 micron is employed. This yields a raw areal density of

$$D_{raw} = \frac{10^6}{0.74 \text{ x } 1.6}$$

$$= 0.84 \times 10^6 \text{ cells / mm}^2 \quad (2)$$

A 5-1/4-inch CD-ROM provides 8 x 10^3 square millimeters of usable recording area. The capacity of the ROM is thus

$$C_{raw} = 0.84 \text{ x } 8 \text{ x } 10^9$$

$$= 6.72 \times 10^9 \text{ cells} \quad (3)$$

For digital data, run-length-limited (RLL) encoding can be used, giving 1.5 bits/cell.

Formatting and error correction to a bit-error rate (BER) of a 1 x 10^{-15} requires an overhead of about 50%. The number of bits/cell is thus

$$N = 1.5 \times 0.5$$

$$= 0.75 \text{ bits/cell} \quad (4)$$

The net user capacity is thus

$$C_{user} = \frac{6.72 \text{ x} 10^9 \text{ x } 0.75}{8 \text{ x} 10^6}$$

$$= 630 \text{ MB} \quad (5)$$

High Density Encoding

Two state-of-the-art techniques have been evaluated for the encoding/decoding circuitry:

(a) Light Intensity Modulation (LIM) - Asahi[2] has demonstrated that it is feasible to reduce the spot diameter by as much as one-sixth that previously realizable for an IR laser, and the track pitch to 0.87 micron, thus theoretically increasing the raw storage capacity of a 5-1/4-inch CD-ROM to as much as 10 Gigabytes. This was accomplished by modulating the light intensity of the laser, using feedback to allow operation higher up on the Gaussian curve. To achieve this density in practice, however, would require a shorter-wavelength reading laser and extremely high mechanical tolerances.

Solid-state blue lasers are under development by several companies;[3] however, they are not expected to be commercially available for several years. However, green lasers are becoming available and should be able to resolve cell lengths in the order of 0.47 micron. This is also more practical mechanically.

Assuming a green laser, and assuming the bits/cell of equation (4), the user bit length using LIM would be:

$$d_{LIM} = \frac{0.47}{0.75}$$

$$= 0.63\ \mu \qquad (6)$$

Using Asahi's track spacing of 0.87 microns, this would give an areal density of

$$D = \frac{1}{.63 \times 0.87}$$

$$= 1.8\ \text{Mb/mm}^2 \qquad (7)$$

(b) Mark Edge Recording - SOCS Research[4], Los Gatos, California, and Sony[5] have demonstrated the ability to write three bits on both the leading and trailing edges of the cell (see Fig. 1). Primelink has taken a license under this patent. Using an IR laser, Primelink has demonstrated:

- a track width of 0.87 microns
- a cell with 6 bits on 1.67-micron centers gives an average bit length of

$$D_{min} = \frac{1.67}{6}$$

$$= 0.28\mu \qquad (8)$$

Using the Sample Servo method for tracking in place of grooves, a track pitch of 1.2 microns was achieved. This gives a raw areal density of

$$D_{raw} = \frac{10^6}{0.28 \times 1.2}$$

$$= 3.0 \text{ Mb/mm}^2 \quad (9)$$

The Cartridge/Drive System

As described above, the raw areal densities achievable using production heads and state-of-the-art encoding techniques on 5-1/4-inch disks, have been demonstrated to be between 1.5 to 3.0 Megabits per square millimeter.

Primelink has developed a digital video optical recorder using the Mark Edge Encoding method on phase change (reversible) and ablative (archival) media. To provide "high fidelity" video graphics to the PC market, it was assumed that at least VGA resolutions of 640 x 512 pixels/frame are needed. To upgrade NTSC and VGA to SVGA resolution and provide for HDTV quality for ultimate home entertainment systems, two proprietary DSP algorithms were used to quadruple the pixels to 1280 x 1024. 8 bits/pel were used for luminance, 4 bits/pel for each of the chrominance pixels. From subjective tests using a simple, proprietary, lossy compression algorithm, it was determined that compression ratios of 10:1 would yield decompressed images subjectively virtually indistinguishable from the original.

Using the above parameters, the required user capacity/frame during transmission and storage is

$$C_{user} / \text{frame} = \frac{640 \times 512\,(8 + 4 + 4)}{10}$$

$$= 0.52 \text{ Mb/frame} \quad (10)$$

For full motion, 30 frames/sec. are required. The average bit transfer rate is thus:

$$\text{BTR} = 0.52 \times 10^6 \times 30$$

$$= 15.7 \text{ Mb/s} \quad (11)$$

$$C_{user} /\text{hr.} = \frac{15.7 \times 10^6 \times 3600}{8 \times 10^9}$$

$$= 7.1 \text{ GB/hr.} \quad (12)$$

Combining equations (7), (8), and (12), and allowing 50% overhead for error correction and formatting, the recording surface area required, depending on the laser/media required, is:

$$A/hr. = \frac{7.1 \text{ x } 10^9 \text{ x } 8}{(3.0 \text{ to } 1.8) \text{ x } 10^6 \text{ x } 0.5}$$

$$= (3.8 \text{ to } 6.3) \times 10^4 \text{ mm}^2\text{/hr.} \quad (13)$$

Background

Using 5-1/4-inch CD-ROM disks with a useful area of 1 x 10^4 square millimeters, from equation (13), the number of disks required would be:

$$N = 3.8 \text{ to } 6.3 \text{ disks/hr.} \quad (14)$$

This is not an attractive solution for digital video, for the following reasons:

1. To be a next-generation (full bandwidth digital) version of SVHS (analog) recorders, the capacity should provide for at least 5 hours. 20 and 40 CD-ROM disks or two disks, requiring a stackloader, 15 to 20 inches in diameter would be needed.

2. Even the 5-1/4-inch drive form factor is too large for lap-top computers and hand-held camcorders. A single standard for universal application would not be possible. This is a requirement for the Primelink system.

For 15.7 megabits per second transfer rate, 50% overhead, from equations (6) and (8), the required beam writing velocity is:

$$V = 15.7 \, (0.28 \text{ to } 0.63) \times 2$$

$$= 10 \text{ to } 20 \text{ m/s} \quad (15)$$

and the total capacity required is:

$$C_{min} = 7.1 \times 5 = 35.5 \text{ GB (use 36 GB)} \quad (16)$$

While this writing velocity is not difficult to achieve with rotating disks and stepped laser-optical heads, disks have been shown above to be impractical for our purposes because of their limited capacity. To achieve the required storage area, especially in a 3-1/2-inch form factor, a tape system became mandatory.

Tape

Known attempts to achieve such optical beam writing velocities using conventional tape drives have all employed scanning devices of one type or another:

(1) Rotating scanners:

Many historical attempts have been made using rotating prisms, lasers on head-wheels, etc. They have invariably failed to reach the market in small, modest-cost systems because of the problem of tracking to the tolerances of laser writing.

(2) Solid-state scanners

LaserTape and others have attempted use of solid-state scanners without commercial success, because of difficulty in achieving the required scan angle in compact-geometry systems, as well as in tracking lateral tape skew.

(3) Linear-motor scanners

CREO is the only company which has achieved substantial sales with an optical tape recorder. Using a linear motor-driven platform on which 16 writing and 32 reading lasers are arrayed, a stationary field of 35-mm. tape is scanned, after which the tape is incremented to the next field. The system is mechanically massive, and sells for about $250,000 CDN. This approach offered no solution for the Primelink project.

The Newell II (NII[*]) Tape Cartridge[6] can easily achieve the required writing velocities without use of an intermediate scanner, and could have been used for this application. The author demonstrated such a cartridge at Newell Research Corp., using 100 meters of 8-millimeter ICI optical tape on 25-micron basefilm, thus providing 8×10^5 square millimeters of surface area at tape speeds to 1000 inches per second. This would potentially provide raw capacities of

$$C_{NII} = \frac{(1.8 \text{ to } 3) \times 10^6 \times 8 \times 10^5}{8}$$

$$= 180 \text{ to } 300 \text{ GB} \qquad (17)$$

for video recording times of

$$T = \frac{180 \text{ to } 300}{7.1}$$

$$= 25 \text{ to } 42 \text{ hours} \qquad (18)$$

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[*] Trademark

Such a system was an "overkill" for the proposed Primelink project, however, and would be more expensive than desired because the cartridge must be reversed at beginning and end of tape. The pulse-power of the motor-drive system required to reverse the system within a time interval that could be economically buffered for continuous video, would be high.

The Newell Opticel[7]

The low tape consumption required for the Primelink project suggested the use of an endless tape loop in a "scramble bin." Such a loop in concept is much simpler than the NII cartridge, in that no tape drive belts or tape reels are required within the cartridge (see Figs. 2,3).

While endless loop systems are well known in magnetic tape systems, the unique problems of an optical tape system using a loop were not trivial, due to the following factors:

- The loop must revolve at high speeds, thousands of times during each record/play cycle.
- The optical recording surface must not be fogged during the life of the cartridge (hundreds of thousands of passes).
- Due to the sub-micron dimensions of the bit cell, debris must not be allowed to accumulate on recorded surfaces from wear or environmental contamination.
- The film must be coupled to the drive and tensioned precisely in the longitudinal direction (X-axis control).
- The film must be edge-guided with very low edge pressure to avoid edge fatigue (Y-axis control).
- The film must be stable in the axis of the laser optics due to very shallow focal depth of the optics (Z-axis control).

Each of these problems, and the method for dealing with it, is disclosed in several patents pending, available on request under a suitable Confidential Disclosure Agreement.

To achieve five hours of high-definition digital video, 16-millimeter tape was used, and two loop lengths were provided for the two encoding methods:

$$L = \frac{5(3.8 \text{ to } 6.3) \times 10^{-2}}{16 \times 10^{-3}}$$

$$= 12 \text{ to } 20 \text{ m} \quad (19)$$

To achieve long life, bending stresses in the tape were kept within 35% of elastic limits, and no optical surfaces or tape edges touched any other surface. The Opticel case was hermetically sealed and back-filled with one atmosphere of a suitable dry gas. 12.5- micron tape was used.
The above parameters required Opticel case sizes of:

Height:	18.5 mm
Width:	90 mm
Length:	95 mm and 140 mm

The standard Opticel is on the footprint of a 3-1/3-inch floppy disk.

The drive used exactly the same elements as a WORM disk drive:

- Laser head (with Y-Z axis control)
- Drive motor (brushless)
- Control and DSP electronics (ASICs)

3-1/2-inch standard drive dimensions were employed:

Height:	41.3 mm
Width:	101.6 mm
Length:	152.4 mm

An Interchangeable Opticel Using the NII Principle

To achieve much higher capacities, the same cartridge/drive interface geometry of the Opticel scramble-bin cartridge can be employed in an NII-type cartridge (see Fig. 3). This allows a high-performance drive system to be developed that would be downward compatible in writing and reading the Opticel.

The NII development is not within the scope of the present Primelink project. However, this development would be a logical follow-on to the Newell Opticel.

Summary

- The Opticel drive uses the 3-1/2-inch standard form factor for both standard and “stretch Opticels.

- The time to the first bit is less than 5 milliseconds; to the last bit is 1 second for the standard Opticel, 2 seconds for the "stretch" Opticel

- The parts count in the drive is lower than that in a typical 5-1/4-inch WORM optical disk drive.

- Capacity of each Opticel (formatted data with BER of 1×10^{-15}) is 36 Gigabytes for the standard Opticel, and 72 Gigabytes for the "stretch" Opticel.

Two Proposed Petabyte Systems

<u>Based on the loop Opticel</u>

A "stretch" Opticel with MER encoding using 24 meters of tape gives 72 Gigabytes per Opticel. This will fit in a 6-inch drive, with 1-1/2-inch overhang.

For a Petabyte, number of drive modules needed is:

$$\frac{10^{15}}{72 \times 10^{9}} = 13{,}889$$

In a stack loader (see Fig. 4) use:

64 modules/column
8 columns/drawer
3 drawers/cabinet
9 cabinets

This would give dimensions of:

Height:	2.75 m
Depth:	0.813 m
Width:	0.572 m x 9 = 5.15 m

With additional R & D the size and access time can be reduced by using:

- Smaller cells:

  Light intensity modulation, MER encoding
  Short wavelength laser (green or blue)
  Tighter track servoing

  <u>From Asahi predictions</u>:

Minimum cell size: 0.2 μ

Cell spacing: $1.67 \times \frac{0.20}{0.74} = 0.45\mu$

Track pitch: 0.87μ

Equation (9) becomes:

$$D_{raw}' = \frac{6 \text{ x } 10^6}{0.45 \text{ x } 0.87}$$

$$= 15 \text{ Mb/mm}^2 \quad (9')$$

- Thinner tape:

  The limiting factor is the shear strength between coating and basefilm; ie., the capacity is inversely proportional to the basefilm thickness. By using 4-micron basefilm, maximum length in the "stretch" version can be increased, and equation (19) becomes

$$L = 24 \text{ x } \frac{12.5}{4}$$

$$= 75 \text{ m.} \quad (19')$$

- Higher tape velocity:

  Primelink has attained tape velocities of 25 meters per second with no difficulty, giving an access time of 3 seconds to 75 meters.

User capacity/Opticel with loop would thus increase to:

$$C_{user} = \frac{0.5 \text{ x } 75 \text{ x } 15 \text{ x } 16 \text{ x } 10^9}{8}$$

$$= 1.125 \text{ TB} \quad (20)$$

For the Petabyte, number of drive modules would be:

$$\frac{10^3}{1.25} = 889$$

The stack loader would require only two drawers in one cabinet.

Based on the NII Opticel

The NII cartridge with 4 micron tape can store 450 meters of 16-millimeter tape in the standard Opticel case size.

- Again, using proven MER encoding with IR lasers, the user capacity becomes

$$C_{user} = \frac{0.5 \times 450 \times 3 \times 16 \times 10^9}{8}$$

$$= 1.35 \text{ TB} \quad (21)$$

Maximum access time would be 18 seconds. Number of drive modules for a Petabyte would be

$$\frac{10^3}{1.35} = 741$$

Again, two drawers in one cabinet would be required.

- Using LIM encoding with green lasers, the user capacity could be theoretically increased fivefold to 6.75 Terabytes, reducing the number of modules to 148, thus reducing cabinet dimensions to, say

Height:	1.60 m
Depth:	0.813 m
Width:	0.470 m

Its volume would thus be 9 cubic feet.

References

1. Mitsubishi ME3H1.

2. I. Morimoto et al., “Ultrahigh Density Recording Using Overwritable Phase Change Optical Disk,” *SPIE Proceedings*, Feb., 1992.

3. W.J. Kozlovsky et al., “Optical Recording in the Blue Using a Frequency-Doubled Diode Laser,” *SPIE Proceedings*, Feb. 1992.

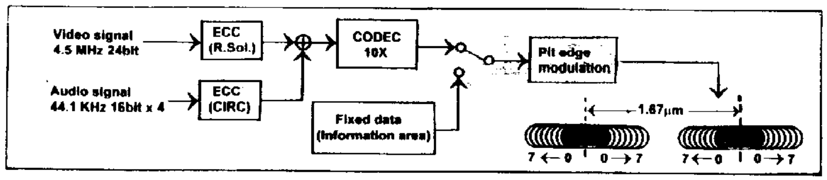
4. U.S. Patent No. 4,736,258, “High Density Storage of Information on a Compact Disc.”

5. S. Kobayashi, J. P. de Kock, T. Harigome, H. Yamatsu, H. Ooki, “High Density Optical Disk Recording by Pit Edge Modulation,” Corporate Research Laboratories, Sony Corporation.

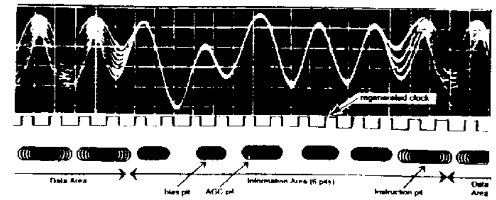
6. U.S. Patent No. 4,172,569, “Tape Transport System With Peripheral Belt Drive.”

7. U.S. Patent Pending, Primelink Technologies Inc.

FIG. 1: PRIMELINK MARK EDGE RECORDING FORMAT



Source: Primelink Technologies Inc.



Source: Sony Corp.

FIG. 2: SCRAMBLE BIN OPTICEL

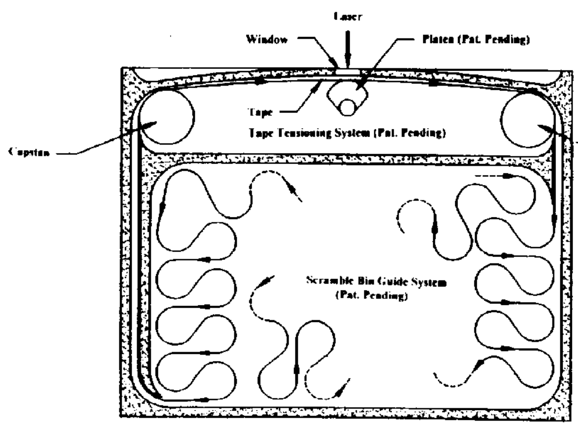


FIG. 3: NII PRINCIPLE OPTICEL (4-HEAD SYSTEM)

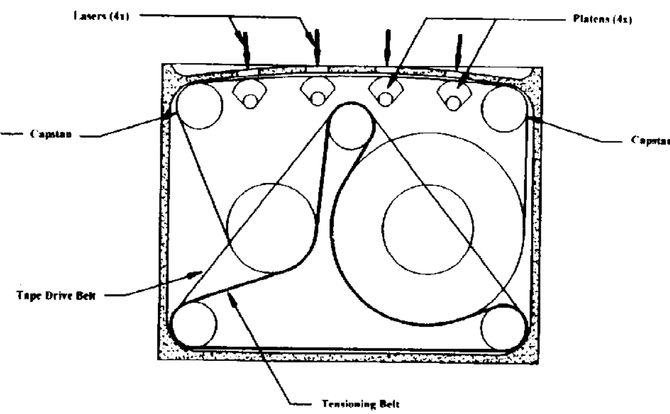


FIG. 4: PETABYTE MASS MEMORY SYSTEM

Proposed by Primelink Technologies Inc.