Laser recording unit for high density permanent digital data storage

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INTRODUCTION

The Laser Recording Unit designed and developed by Precision Instrument Company provides a means for reliably and permanently recording and reproducing digital data.

The Laser Recording Unit uses a new type of permanent recording process which employs a laser to vaporize minute holes in the metallic surface of the recording medium. In this manner digital information is recorded in parallel data tracks along the length of a recording medium strip. The tracks are spaced on the order of five to ten microns (micrometers), center-to-center; each track is composed of bit cells three to five microns in size. For recording or reproducing sequential tracks of digital data, the maximum transfer rate of the Laser Recording Unit is approximately four million bits per second, with an average unrecoverable error rate of one in $10^8$ to $10^9$ bits, depending on the data density selected.

The Laser Recording Unit includes a programmable Recorder Control Subsystem which can be designed to provide a hardware and software interface compatible with a specified computer system.

The major benefits offered by the Laser Recording Unit as a mass digital-data storage unit are summarized below:

1. Permanent Storage: Data do not degrade over a period of time of the order of years.
2. Compact Storage: Data are stored at a density approximately 250 times greater than that of digital magnetic tape.
3. Unlimited Readout: Data can be repeatedly readout for long periods of time without reduction in quality or damage to the record.
4. Recording Verification: Essentially error-free data records result from the simultaneous read-while-write verification capability that is unique to the laser hole-vaporization method of permanent recording.
5. Low Error Rates: The average unrecoverable error rate is approximately one in $10^8$ to $10^9$ bits.
6. Economical Data Storage: Recording of large quantities of data on the Laser Recording Unit and permanent storage of the data in PI Record Strips significantly decreases the cost-per-bit of recording and storage imposed by existing methods.

Laser recording unit design

The Laser Recording Unit employs a special recording medium in strip form which is automatically mounted on a precision drum assembly. Using digitally modulated incident coherent laser radiation, diffraction-limited marks or holes, each representing one bit of information, are permanently evaporated in a track pattern in the recording medium as the medium and mounting drum rotate under a focusing microscope objective. Thus, parallel data tracks are recorded transversely along the recording medium.

The major parameters which must be considered in the design of a Laser Recording Unit are:

1. Optical mode of laser beam.
Diameter and divergence angle of the beam.

(3) Diffraction limits of the optical system which images the laser aperture on the recording medium.

(4) The thermodynamics of the hole-forming vaporization process.

(5) The kinematics of the optical scanning and mechanical transport of the recording medium.

(6) Characteristics of thin metallic films, deposited onto flexible substrates.

A typical embodiment of these principles is the prototype demonstrator unit in operation at the Research Laboratory of the Precision Instrument Company since January 29, 1968 (see Figure 1).

The recording/reproducing laser is a cw argon II ionic laser operating in zero-order, single-mode (TEM_{00}) at a maximum power of one watt over all wavelengths. The wavelength of 4880 Å has a maximum intensity of 0.40 watt and is separated from the total output of the laser by means of multiple-layer dielectric filtering.

The light beam emitted from the laser passes through a NBS-calibrated thermopile to determine the total emitted laser power and enters the electro-optical modulator which is a Pockel's cell, which provides changes of the refractive index of the modulator medium (KD*P) as a function of the sine of the applied electric field intensity. The physical configuration of this portion of the equipment is shown in Figure 2.

After passing the electro-optical modulator and adjacent polarization analyzer (Glan prism), the laser beam enters track widening optics which include a beam folder and an aspheric reflector spreading the wavefront of the laser beam in one dimension. Thereafter, the laser beam passes an optical beam splitter which separates the beam incident to the recording medium from the beam reflected. A periscope adjusts the laser height to that of the recorder so that the laser beam reaches the mirror of the tracking galvanometer. The light reflected back from the recording medium returns again to the optical beam splitter, yielding two separate beams for photoelectric signal detection and error detection, respectively. The appearance of this portion of the equipment is shown in Figure 3.

The recording/reproducing process may be interpreted as follows. Assuming a laser beam is incident to the recording medium at a relative intensity level of 100 percent, reflection and diffraction of the beam occur at the medium. In the absence of a recording, approximately 50 percent of the incident laser power is reflected back towards the incident laser direction. Assuming now the incident laser intensity to be strong enough to vaporize a diffraction-limited section of the recording medium, during the recording process the reflectivity of this area is reduced from 50 percent down to five percent. Hence, separation of incident and reflected light in the path of the laser beam, utilizing a beam splitter, yields an intensity variation of the reflected signal between 50 percent and five percent, thus producing the necessary photoelectric signal output.
for reproducing. Figure 4 is a diagram indicating this relationship.

Figure 5 is a block diagram of the equipment used with the prototype Laser Recording Unit to produce test recordings and evaluate retrieval capabilities. In operation, an unrecorded region suitable for ten or more data tracks is manually set up on the record strip surface. For each track to be recorded, a known arbitrary number is set into the manual count selector switches. The unit is placed in record mode and, when a drum-actuated home signal next occurs, the data are recorded on the selected track. To verify retrieval, the tracking servo is commanded to follow this recorded track and repeatedly read out the data thereon. The output of the data sense system is then transmitted to the data output counter, during each drum revolution, and, upon completion of the track readout, this value is transmitted to a parallel identity comparator, to be matched against the state of the count selector switches. Each time an error occurs, as indicated by failure of identity comparison, a count is transmitted to an error counter.

A typical count entered on a data track is about 5,000 repeated data bit patterns. With the drum operating at a nominal rate of 30 RPS, the unit in read mode will repeatedly read and check about 150,000 such bit patterns per second. Repeated runs over a period of several weeks established an average of about 700 seconds of operation between errors, or an error of about one in $10^8$ bits.

High density data storage system

Such a system is composed of a Laser Recording Unit and a Recorder Control Subsystem and is typically operated as a peripheral device to a large computing or data processing system.

Laser recording unit

The Laser Recording Unit functionally is a rotating memory with a single movable head for permanent data recording and nondestructive data reproduction. The standard recording-medium strip used with the device is approximately 4.75 by
Each standard recording-medium strip can provide a total net data capacity of \(1.96 \times 10^9\) bits, or 245 million bytes. This capacity will be provided with a bit-cell size of four microns, allowing a bit density of 6,350 bits per inch along each data track and thus approximately 198,500 bits per track; a center-to-center track spacing of eight microns will provide a track density of 3,175 tracks per inch of recording-medium width. Since about 11 percent of the recorded bits will be used for clocking and control purposes, about 175,000 bits per track will represent the net data-recording capacity. With about 11,200 tracks recorded on each strip, the total net data capacity of the strip will be \(1.96 \times 10^9\) bits or 245 million bytes. For this standard record strip a data transfer rate of 4 million bits, or 500,000 bytes per second can be obtained at a drum rotation speed of 22.9 rps (43.5 milliseconds per revolution). This configuration provides a bit error rate of approximately one bit in \(10^8\) data bits.

For convenient storage and handling, the recording medium strips are provided with a protective package called a PI Strip Pack. The Strip Pack for a standard record strip is approximately 5.0 by 32.0 by 0.25 inches in size.

Figure 6 is a perspective view of the proposed physical design for a production model of the High Density Storage System incorporating a Laser Recording Unit, configured for use in a computing room environment.

Figure 7 is the overall Laser Recording Unit block diagram. It illustrates the major equipment groups necessary to guarantee subsystem performance. The track-position and carriage-position servos ensure proper positioning of the read and record laser beam. The focus position control group maintains proper objective lens focus position over the full drum width. Laser recording power level is maintained by the laser intensity control group which also provides attenuation of the laser power for the Read Mode. The control logic group provides synchronization, sequencing,
and selection signals for automatic internal control of the subsystem, as well as input/output interface to the Recorder Control Subsystem.

The drum motor servo speed control group provides precise control of record/read drum rotational velocity. The maintenance panel provides controls, indicators, and meters required for routine maintenance and calibration. The data sense group provides media and record verification, as well as data readout. Figures 8A through 8D are block diagrams depicting the functions of the above groups.

**Electronics enclosure**

The electronics enclosure is located in the laser recorder console cabinet. The cabinet also supports the precision mounting plate, which provides for the mounting of the laser and optics. The top of this cabinet is structurally reinforced to accept the shock mounts holding the precision plate. The base is sufficiently strong to permit the use of a fork lift for moving the laser recorder console. The cabinet consists of four 19-inch standard bays with removable covers or both front and back access. The bay itself is 96 inches long by 32 inches high by 34 inches deep. The strip-pack loading surface is located approximately 38 inches from the floor, and the overall dust cover maximum height is 56 inches from the floor, providing a convenient strip-pack loading height for a standing operator. (Reference Figure 6A.)

The laser power supply and heat exchange (used for cooling...}

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**FIGURE 7**

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From the collection of the Computer History Museum (www.computerhistory.org)
the laser head) will be located in a separate cabinet (not shown.) The space provided in the console cabinet of the Laser Recording Unit is used for the packaging of the signal and control electronics required by the laser recorder, the Recorder Control Subsystem, and the cooling and air-filtration system required for the console (i.e., dust removal in the optical area).

**Recorder control subsystem**

The Recorder Control Subsystem is physically packaged as part of the Laser Recording Unit. A block diagram of the subsystem is shown in Figure 9. The major element of the subsystem is a special-purpose programmed processor. One output of this processor is to the data channel interface unit of the specified main computing system of which the High Density Storage System is a peripheral device. Other interfaces are to local peripherals of the programmed processor. A final and important interface is to the Laser Recording Unit itself. A block diagram of this interface is shown in Figure 10.

The Laser Recording Unit recording process is conducted on a serial bit-by-bit basis which requires that information transmitted from the Recorder Control Subsystem for recording be not only serialized, but also logically interleaved with two auxiliary signals; the clock and verify signals. The principal objective of the clock is to place, with the stored information, a timing reference for retrieval synchronization. The verify signals will be of two types: the segment (16-bit) verify signal which determines the recording validity of
the preceding data segment, and the check sum
verify signal, which is a two-character (16-bit)
character-oriented accumulated sum verification
for each 256-character string.

During retrieval, the Recorder Control Subsys-
tem is required to: (1) determine validity and
destination of retrieved information; (2) perform
remedial actions and return to normal operation
after completion of such actions; and (3) logically
remove all clocks, verify and check-sum bits from
the serial data while maintaining smoothness of
data flow.

Since the function of the Recorder Control Sub-
system is to provide communications between the
controlling computer complex and the Laser Re-
cording Unit, it is this unit which must be adapt-
able to the interface requirements imposed by
various computers. The Recorder Control Sub-
system will accommodate various computer input/
output requirements by changing the input inter-
face and the control programs in the programmed
processor unit. The remainder of the Recorder
Control Subsystem will remain virtually un-
changed regardless of the computer complex
utilized.

Since a major goal in the design of the Laser
Recording Unit—and consequently the Recorder
Control Subsystem—is to provide a structure with
maximum dependability, additional auxiliary logic
is included in the Recorder Control Subsystem to
perform a thorough closed-loop diagnostic test of
all logical features and characteristics.

During a diagnostic mode, the auxiliary diag-
nostic logic sets up a logic configuration simulating
b = logical value of data bit to be recorded
b_r = logical value recorded

FIGURE 10

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a recording-reading operation; i.e., as data are re-
ceived from the data channel, they follow a nor-
mal-sequence recording path; however, the data
transmission is diverted from the Laser Recording
Unit and instead follows a closed loop within the
Recorder Control Subsystem. A simulated retriev-
al is performed in essentially every respect, which
concludes with the data being sent back to the
computer to be examined for evaluation of Re-
corder Control Subsystem operation. After suc-
cessful completion of this diagnostic procedure, a
further procedure for test of the Laser Recording
Unit may be initiated. With the aid of an opera-
tor, PI strip packs may be inserted in the Laser
Recording Unit under order of a diagnostic pro-
gram, known synthetic data recorded, and then
successfully read back for a diagnostic check of
the complete Laser Recording Unit.

Recorded data format

The data recorded by the Laser Recording Unit
will be placed on the high-density recording me-
dium through incident coherent laser radiation,
causing diffraction-limited holes to be permanently
evaporated in the recording medium in a pattern
which represents the binary input data.

The recorded data will be placed in tracks run-
ning parallel to the length of the medium. In a
typical organization of the recorded data, these
tracks will be separated by an 8.0-micron center-
to-center spacing: this will allow over 3000 tracks
per inch of medium width. The data bits to be
written along these tracks will be spaced on 4.0-
micron centers thus allowing for about $2.0 \times 10^5$
bits to be recorded on any given track. A section
of typical laser recording, greatly enlarged, is
shown in Figure 11.

A prime consideration associated with such a
recording technique is the format or organization
of the data so recorded. A format control portion
of the Recorder Control Subsystem controls the
format of the data as they are recorded.

Figure 12 illustrates the track-oriented record-
ning organization employed to combine all auxiliary
recording signals, such as time-synchronizing
pulses, diagnostic patterns, and track identifica-
tion with the data to be recorded from the com-
puter data channel. The following paragraphs
describe the various areas shown in Figure 12 for
a typical data track.

Timing synchronizing sector

The timing synchronizing sector will be re-
corded with two alternating patterns: namely, all
ones and character-separated ones. The initial all
ones are employed to accelerate the synchronism
of the read clock with a voltage-controlled clock
(VCC) by performing repeated comparisons to

![FIGURE 11](From the collection of the Computer History Museum (www.computerhistory.org))

![FIGURE 12](From the collection of the Computer History Museum (www.computerhistory.org))
accurately measure their time occurrence difference, thus generating a fine control of the VCC period. The character-oriented clocks will be compared with a counted-down clock derived from the voltage-controlled oscillator clock to establish a synchronism within longer intervals and generate a secondary feedback quantity to obtain further VCC period control adjustments, if necessary.

Diagnostic pattern

After timing synchronizing patterns are recorded, a diagnostic pattern will be recorded. This diagnostic pattern will be employed to determine if the retrieval logic structure is performing correctly (i.e., data retrieval, holding, verification, data stripping, and transmission are exercised by the diagnostic pattern to search for any probable logic or circuit anomalies).

Track identification

A track identification number will be recorded to aid in determining the location of a selected track during data retrieval. During recording, if frequent errors occur, remedial action will be initiated which will record an identical track identification pattern in the adjacent track and repeat the core memory block transfer into the newly identified track. During reading, the search for a track position is greatly aided by the track-identification patterns which will avoid ambiguous track determination.

Data block

The data block will be a block of information which contains the actual data to be recorded from magnetic tape. This block will be of length equal to 128 16-bit verified segments (i.e., if a 16-bit segment verify position indicates an error within the segment occurred during recording, this segment is considered invalid or nonexistent).

Check sum

The check sum locations contain an algebraic sum derived by a process of repeated additions of the values of the recorded valid segments. The algebraic check sum is a 16-bit segment which will be transmitted to the computer only during diagnostic modes. During reading, the retrieved check sum will be compared with a calculated check sum.

Other formats

It can be seen that a data track may be divided into separate sectors with capability of acquisition of track at each sector-start point, rather than for an entire track. Many such modifications may be implemented, depending on record size and format of input data.

PI strip pack

The flexible mylar high-density recording medium strip, which is 4.75 inches wide by 31.25 inches long by 0.010 inch thick, is contained in its strip pack, which is 32 inches long by 5 inches wide by 0.25 inch thick (Ref. Figure 13). The Strip Pack contains edge index slots which prevent the data surface of the recording medium from contacting the Strip Pack's protective surface. Protective caps seal each end of the Strip Pack. The recording medium may be inserted from either end.
System capabilities

Loading

Since the record strips are demountable, any number of record strips can be used to compose a mass data file. To access a block of data in such a file, the PI Strip Pack containing the record strip that holds the required data must be identified. Typically, this action is performed by the data-processing system of which the Laser Recording Unit is a peripheral device: the action is initiated by an input request, which is followed by computer lookup in an index file and then a printout or display for an operator. The operator then selects the requested strip pack from file and places it on the Laser Recording Unit in readiness for loading.

The Laser Recording Unit automatically loads the record strip onto the drum surface and confirms that the requested record strip is correctly loaded. Next, a mechanical carriage-positioning unit, operating under servo control, translates the record/reproduce head to the approximate track address requested by the computer. Finally, an optical tracking servo selects the exact track desired; when the start position for the requested data record is reached, data transfer occurs and continues at the 500 kilobyte rate (except for short gap times) over all sequential tracks containing the requested data.

On the basis of evidence from experiments involving repeated loading and unloading of record strips on a breadboard model of the drum mechanism, it is expected that a particular record strip repeatedly accessed and loaded will return to the same position on the drum periphery within 2 Mils or approximately 50 Microns, maximum. This is well within the tracking range of the galvanometer servo.

The strip-loading process requires about 15 seconds after the operator places the requested strip pack in the load slide of the Laser Recording Unit. However, after a selected record strip is loaded onto the drum, access to each additional block of data on the same strip can take place in less than 400 milliseconds.

Timing

Access motion time

Access motion time is the time required to position the track access mechanism on the LRU to the track containing a specified record on an already mounted and rotating record strip.

In the LRU, the record/read head is positioned to the selected track by a carriage position servo. This unit uses a linear mechanical carriage which is supported by precision ball bushings and driven from a servo motor, through a precision steel belt. A linear incremental encoder plate provides position inputs. For this mechanism, the maximum carriage-positioning time to move from track 1 to track 11,200 on the record strip is less than 400 milliseconds. The minimum access time to move to the adjacent sequential track is less than two milliseconds, and the operation can be accomplished during the gap time at the end of each track on the record strip.

Head selection time

The LRU has a single record/read head mounted on an optical tracking servo. Upon arrival of the mechanical positioner to within two mils of the desired track location, the galvanometer-controlling optical tracking servo will access the track at the center of the field to the objective lens. This field is of the order of 100-200 microns and will cover 10 to 25 tracks, depending on recording density.

At N points around each track the track address number will be recorded, and an optical tachometer on the drum will indicate these locations or sectors. Within 1/N revolution, the track address will be determined.

Due to possible positioning error in the carriage mechanism, the track initially accessed by the optical servo may be one or two tracks distant from the track actually addressed. If the accessed track address is wrong, the optical servo then slews to the correct track; again a wait equivalent to 1/N of a drum revolution may be required to confirm the address. If the specified data were passed in the process, a rotational delay ensues. The galvanometer has a positioning accuracy of one micron and requires about two milliseconds slew time to reach the new track.

Rotational delay

Rotational delay is the time required after the proper track is reached for the correct data to rotate to the read/write head for the start of data transfer.
Assume the LRU device described above has just entered one sector of the specified track and determined that the track address was correct. If the sector contains the desired data, data may be read out immediately.

If the device has entered the wrong sector, the addressed data will be in one of the other sectors of the track, since the machine is on the correct track. Thus, a maximum rotational delay can occur equivalent to \((N-1)/N\) percent of a drum revolution. With \(N=8\) and a nominal revolution time of 43.5 milliseconds, there is a total possible maximum lapse of 51 milliseconds for head selection and rotational delay.

**File updating**

Since the Laser Recording Unit is a permanent recording device, with nondestructive read, data once written cannot be erased and rewritten as in a magnetic memory. For a large direct access file one convenient organization is that the file master index in key number order be stored on disc pack units under control of the main processor. When it is desired to delete or modify a record in the mass store, the record data are pulled out to the core memory in the recorder control unit, the data modification made, and the entire record rewritten at a new vacant location on the LRU record medium. The new track address is then placed in the disc-mounted index in place of the obsolete address, and this data item will be thereafter accessed at the new location in the mass store.

Where a data record has continuing transactions, which do not obsolete the remainder of the record, at the time of initially placing this record into the mass store, blank spaces may be left, and a local address stored in the disc-mounted index. Then when a transaction is to be added to a mass store record, the address is read from disc, incremented by one and returned, and the mass file track and sector address read, access obtained, local address used to count down the record, and the new transaction written. This may be repeated until the local address regions initially allocated to this record are all filled. Then, either a transfer address to a new mass store track may be utilized for continuation of the record, or the procedure of completely transferring the record to a new location in the mass file may be used.

In a system which contains more than one LRU, the mass file may from time to time have all obsolete material deleted, by passing through the current disc index in key order, and rewriting only those portions of the original mass file which are currently accessible. Also, a special mark or code can be placed on any data record in the mass store to cause the readout system to ignore this data, in a manner similar to that used for read-while-write data validation in which any write error causes the data to be marked as invalid, and the recording repeated.

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