

Design Considerations for a Magneto-optic Cryogenic Film Memory

Abstract: It has been shown that certain materials, because of their ability to rotate the polarization vector of plane polarized light, can be applied to very large data-stores. One such material (iron-doped europium oxide) requires an operating temperature below 100 K. To produce an experimental device with superior cost/performance, a rotating disk file configuration was chosen. In developing this machine there were many unique demands placed on bearing technology, vacuum technology and system configuration. These and some material considerations, as well as the novel engineering features, will be described.

Introduction

Some early work by Fan, Greiner and Ahn [1,2] showed europium oxide films to be attractive for use as the storage medium in potentially very large memories ($\approx 10^9$ B). Size alone does not make a system using such films unique, but by employing an optical array transducer (gallium arsenide lasers) [3] it appears possible to provide a file with access time as short as that of drum memory but at a bit cost comparable to that of disk storage.

Europium oxide film was chosen as the storage medium for this memory because of its extremely large magneto-optic effect and high thermosensitivity. This effect, the ability of the film to rotate the polarization vector of incident polarized light to different orientations dependent on its state of magnetization, is the most pronounced of its kind in any known material. (The Faraday rotation of a 1- μ m thick EuO film is $\approx 50^\circ$.)

To be useful in such applications, these films must be refrigerated to temperatures below 100 K. Producing such a cryogenic environment dictates a system that has minimal heat losses. Cryogenic refrigeration on a per-watt basis is costly and the physical size of the cooling unit becomes prohibitive for convenient use. Input power is also a consideration, since the efficiency of this sort of refrigerator is less than 5 percent. Vacuum insulation must be provided for the cold components and this, coupled with the consideration that ordinary lubricants do not function at such low temperatures, implies that rotating seals and conventional bearings cannot be used.

In this paper we report the design and construction of a device resembling a disk file that demonstrates the

feasibility of a high-speed thermomagnetic recording scheme, overcomes the outlined difficulties and allows the use of Kerr or Faraday rotation to read thermally recorded data.

Principles of operation

The film is initially saturated by the magnetic field produced by an electromagnet (see Fig. 1). The direction of magnetization is in the plane of the film. After saturation, the field is reversed and maintained at a level that by itself is incapable of reversing the remanent magnetization in the film due to the film's coercivity. A beam of radiant energy generated by the laser is focused on the film and produces local heating. The rise in temperature reduces the coercivity of the film such that the reversed bias field causes the heated region to switch. When the beam is turned off, the small region of reversal remains.

To interrogate the film, a source of plane polarized light is caused to impinge on it. (The source of polarized light is the same laser as that used to write.) The output of a solid state laser is generally proportional to its input power, and it is therefore a simple matter to operate the laser at such a level that heating will not produce a temperature rise sufficient to erase a magnetized area. The ratio of writing energy to that required for reading was found to be greater than 5:1.

Since the film rotates the polarization vector of the transmitted or reflected incident beam, a change in amplitude can be produced by allowing the beam to pass through an analyzer. Transmission is shown in Fig. 1, but the same effect could be produced by a detector ar-

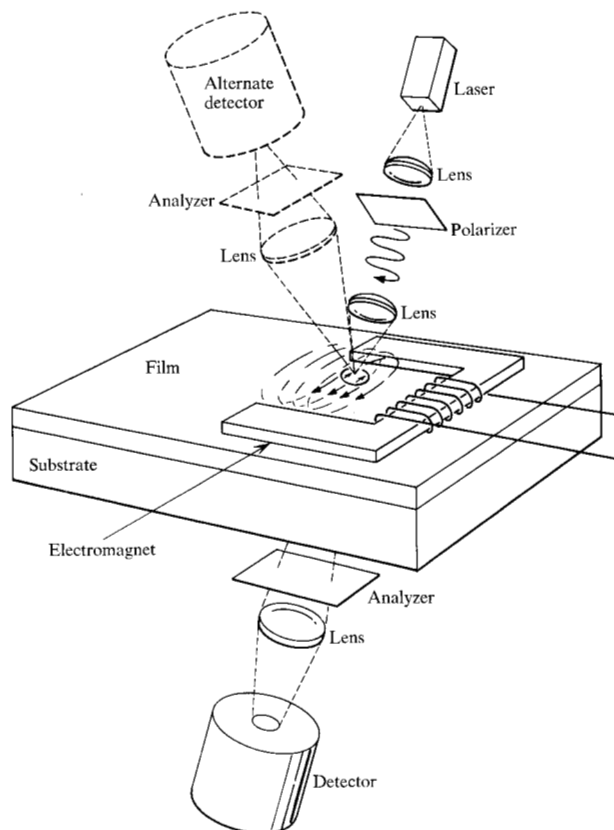


Figure 1 Static magneto-optical reading and writing.

ranged to monitor the reflected beam (dotted lines). The amplitude change is then transmitted to the detector. An extension of the system to the form of a disk file is shown schematically in Fig. 2. In this case a disk coated with the film is rotated past the gap of the bias magnet and information is recorded sequentially on a track by pulsing the light source on and off.

For normal writing purposes in this system it is not necessary to raise the film to its Curie temperature. The combination of the bias field and the reduced coercivity allows reversal of the stored region at intermediate temperatures. Alternately one might use a high energy pulse to reduce the remanence to zero (see Fig. 3). Intuitively one might expect either of these writing processes to be rather slow; however, rates in excess of 5 MB/s have been demonstrated. Reading speeds are determined by the detector bandwidth and the available light energy passing through the film. To briefly summarize the results from a paper dealing with signal-to-noise considerations in this system [4], 25 MB/s is probably the ultimate read rate for such devices.

The lasers, which electrically most closely resemble a pn junction with a barrier potential of about 1.5 V, are

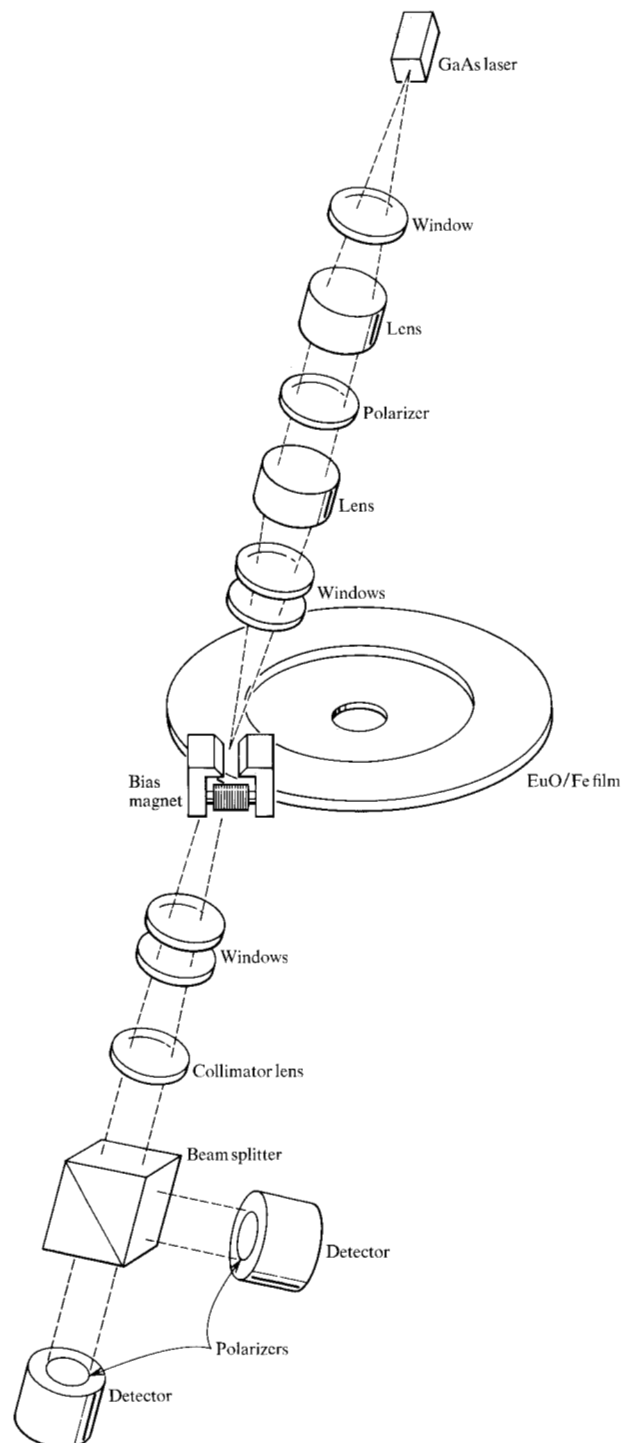


Figure 2 Thermomagnetic writing on rotating disk.

capable of producing light pulses on the order of 1 ns wide. The limiting factor in writing, then, becomes the speed of the switching transistors used for driving the laser array (about one ampere is required for writing) and their associated lead reactance.

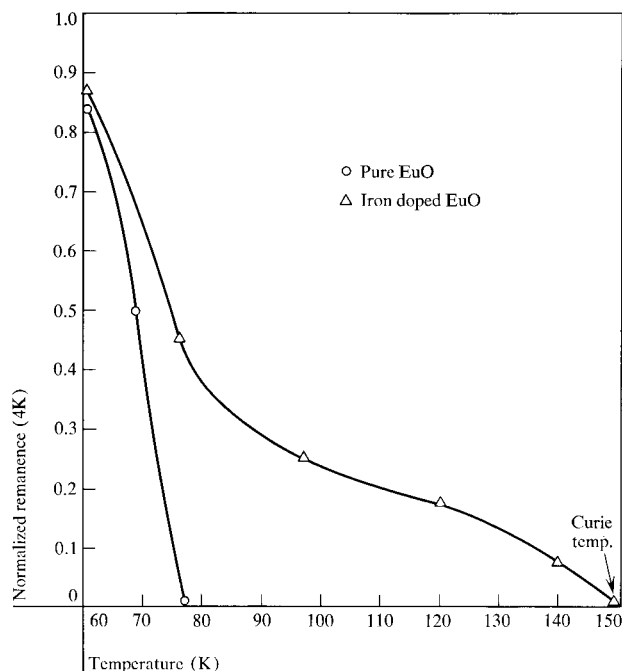
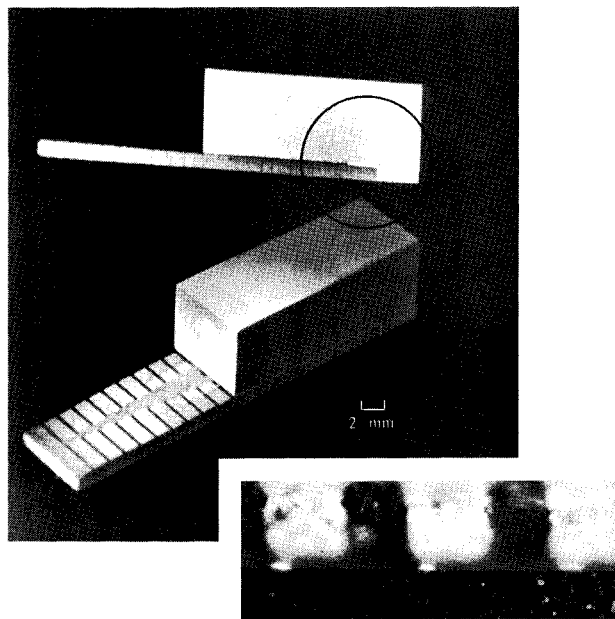


Figure 3 Curves showing remanence changes with temperature in pure and doped EuO films. Faraday rotation follows a similar curve.

Figure 4 Photograph of gallium arsenide laser array as used in the disk file. The circled area is shown in the inset, where the bright spots are electrical contacts to the junctions.



To provide a more efficient utilization of the transducer arrays, each of which is composed of twenty junctions (see Fig. 4), a deflector can be interposed in the optical path as shown in Fig. 5 to move the beams radially. In this manner, depending on the image width, a given laser

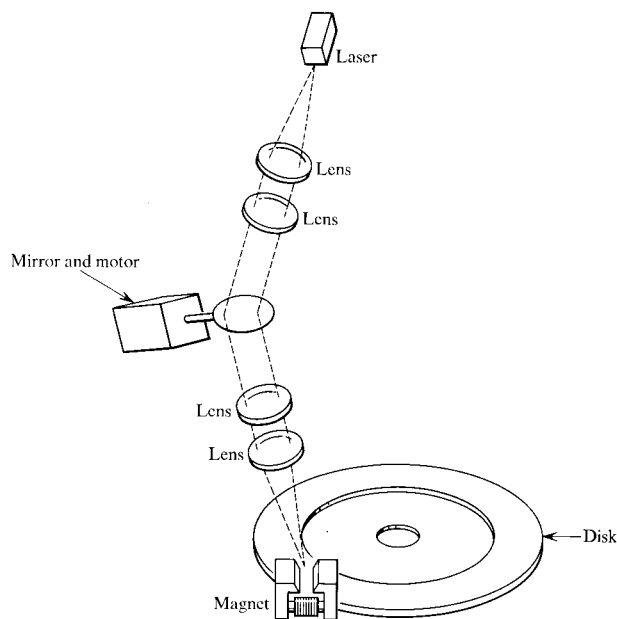


Figure 5 Schematic representation of deflector interposed in optical path to provide multiple track access.

can address the number of tracks determined by the ratio of track-plus-guard-band width to junction spacing. There is an upper limit on such a ratio due to the image aberration introduced by the deflection scheme since, as the deflected field becomes larger, it is difficult to compensate for path length differences in high resolution lenses.

Materials

In any cryogenic apparatus, it is most advantageous to provide cooling by liquid contact. This restricts the range of achievable operating temperatures to within a few degrees of the normal boiling point (NBP) of the available cryogens.

Pure EuO films, whose Curie temperature is about 70 K, then dictate liquid nitrogen (NBP = 77 K) as the cryogen of choice. However, lowering the NBP to less than 70 K requires a reduction in pressure above the fluid to less than half of atmospheric pressure. This would be necessary to bring the film to its linear operating region, but it requires auxiliary pumping with considerable attendant complexity. It was thus deemed worthwhile to search for a means of raising the Curie point of the material, and Ahn [6] has been able to raise it to 150 K by doping pure EuO films with iron. Refer again to Fig. 3, from which it can be seen that 77 K is an acceptable operating point, more than half the remanent field being available for signal conversion. The actual films used in our model have been more fully described elsewhere [7].

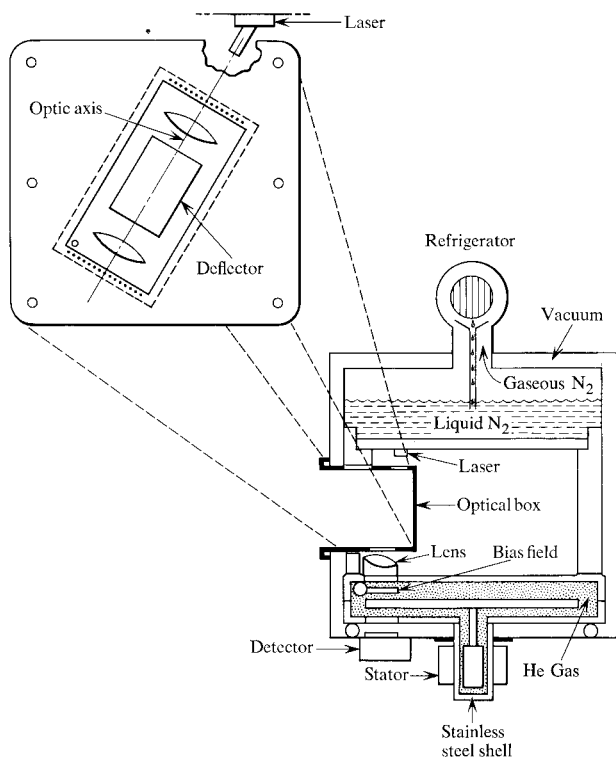


Figure 6 Closed loop cooling technique for sealed disk chamber and lasers.

The importance of having a film that can be operated with liquid nitrogen as the refrigerant is emphasized when one considers that nitrogen is the most easily transported cryogen and the one most easy to handle. It is also the most widely available and has the lowest cost.

Although the cooling system for a disk file would be continuous, a reservoir for providing thermal inertia in the event of power loss is necessary. (The stored information is volatile unless the film is kept below its Curie point.) Liquid nitrogen, whose heat of vaporization is 85 BTU/lb, would allow inclusion of such reservoirs of a size compatible with the overall system packaging. In this connection, it is necessary to observe that LN_2 can be safely evaporated into the normal commercial environment, as would be necessary in the event of an extended power outage.

Disk model

With the two major material choices fixed, an apparatus was designed that would be mechanically reliable. An overall consideration was that the eventual system be field serviceable by personnel with ordinary skills. This meant designing in the necessary accessibility to adjustments and high-risk components. The design that evolved is shown schematically in Fig. 6.

The means chosen for refrigerating the model was to replenish the LN_2 as it was boiled from the reservoir. However, a closed loop system can be made by coupling a continuous cryogenic refrigerator to the liquid nitrogen reservoir. The refrigerator is a mechanical device, electrically driven. Its function is to provide a cold surface at or below the liquefaction temperature of nitrogen gas. The cold surface is in contact with the evolving gas from the reservoir and serves to condense the gas, which then returns to the reservoir as a liquid. The cooling process is thus continuous. The reservoir capacity can be reasonably designed to carry the system load until repairs are made or a data dump effected in the event of refrigeration shut-down. Liquid level control is accomplished by monitoring reservoir pressure so that when the condensing process overtakes the evolution of gas, the reservoir pressure drops, causing the refrigerator to cycle off.

The advantages of physically separating the energy removal process associated with the refrigerator from the actual heat transfer from the memory include vibration isolation and the geometry independence of the refrigerator. There are several configurations of continuous refrigerators that fill the needs of such a system, but these differ radically in shape. Any of them, however, can work with the outlined system, even though vibration precludes any intimate contact with the disk mechanism. It is beyond the scope of this paper to discuss the refrigerators themselves in any detail, but three manufacturers of cryogenic coolers are listed in the references [5].

The disk housing is a sealed chamber supporting the disk rotor and spindle assembly and is filled with gaseous helium to effect heat transfer from the rotating disk. The spindle is supported on specially designed ball bearings, which are dry-lubricated and designed to operate at cryogenic temperatures.

A major mechanical problem was to provide a means for rotating the disk in its sealed housing. To avoid the problems of reliability and frictional loading that are unavoidable in rotating seals, a novel method of driving the disk was constructed. The lower part of the spindle is the rotor of a synchronous motor, and this rotor is housed in a thin, stainless steel shell. The shell is surrounded but not touched by the stator, which creates a rotating magnetic field when excited by three-phase ac current. The rotating field pulls the rotor around in a manner exactly like that of a conventional, synchronous hysteresis motor.

The stainless steel shell is transparent to the field. In this drive the only losses are those from eddy currents in the shell, rotor losses in hysteresis motors being negligible. The thinness of the shell and its low conductivity make the eddy currents immeasurably small, an impor-

tant feature in reducing the dissipation of power as heat. To our present knowledge no rotating seal or other means of drive can approach this design for efficiency or simplicity and still meet the requirement of minimal heat loading in a cryogenic system.

The bearings themselves are commercially available [8] and do not use grease as a lubricant. Rather, the approach is to provide a Teflon separator for the ball bearings that has been impregnated with molybdenum disulfide. As the bearings rotate, minute particles of the separator rub off on them and provide lubrication. The bearings are thus suitable for use in the extreme environment where liquid lubricants do not function. No outgassing occurs with this method of lubrication, and the bearings can thus be located within the disk space without contaminating the disk itself. The amount of free floating particulate matter from separator wear has been empirically determined to be negligible.

Solid-state lasers require cryogenic temperatures to operate, and are attached in our system to the bottom of the heat sink reservoir. The heat from the disk chamber is conducted to the reservoir by a cylindrical pipe that also serves to fix, quite accurately, the distance between the laser platform and the disk. This is necessary, of course, since depth of field for the optical system is of the order of 1 mil. Intervening between the lasers and the disk housing is the optical assembly, which is cantilevered from the outer housing through a cut-away section of the heat pipe. The optics box is vacuum tight and does not touch the heat pipe. It, as well as the drive station, forms part of the outer housing that surrounds and supports the disk chamber and reservoir in a vacuum provided for insulation. All of the optics are at room temperature and pressure, and thus accessible. Adjustments are made with the system running, since no pressure locks are required to maintain vacuum integrity. The coefficients of expansion of glass and metal are different by an order of magnitude, and it is necessary to provide a strain-reducing mount for the entry and exit windows in the disk chamber. This is required not only to prevent fracture of the window but also to eliminate the optical ellipticity that would be produced by any strain on the window. The windows are, of necessity, also hermetic and are described in detail elsewhere [9].

An exit port is provided at the bottom of the outer casing to pass the light transmitted through the disk to the detector. A cut-away drawing of the actual assembled apparatus and some of its component parts, shown in Fig. 7, reveals the relative simplicity of the system.

Performance parameters

The disk in the model had a diameter of 3 in. and was rotated at speeds up to 24,000 rpm, although an operating speed of 12,000 rpm was used in the signal reversal

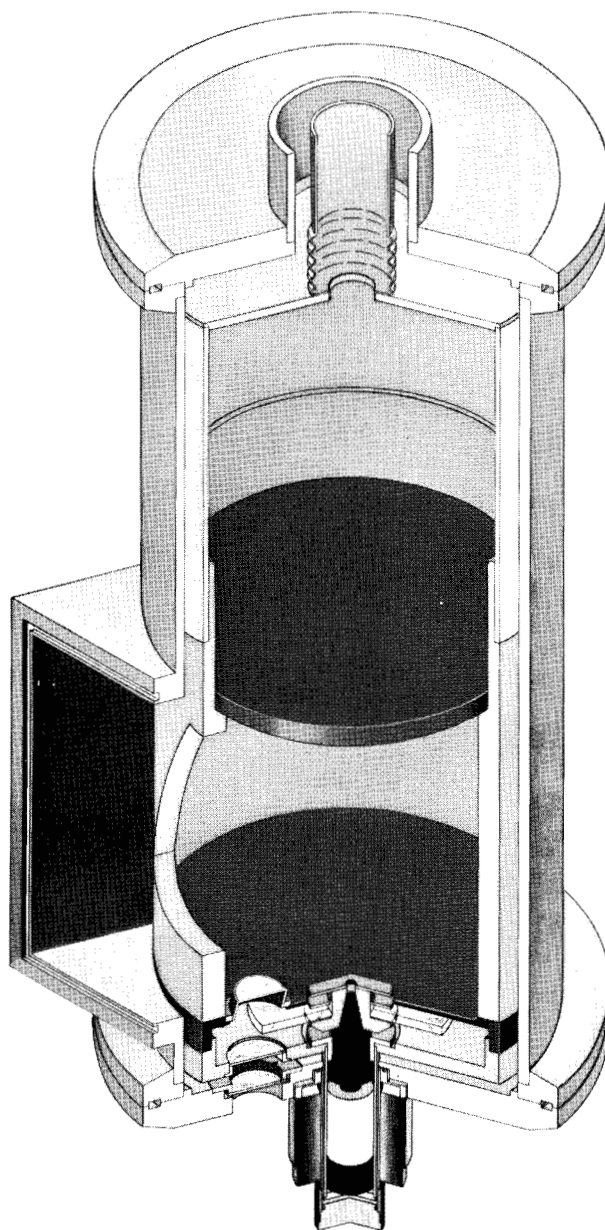


Figure 7 Cut-away scale drawing of 3-in. disk model.

experiments. At this speed, the refrigeration load from all sources was less than 4 watts. Since no attempt was made to minimize radiation losses, it is estimated that this load could have been halved.

There was adequate heat transfer from the disk with a helium pressure in the disk chamber of less than $100 \mu\text{m}$, and thus rotational friction load would be approximately 50 watts. Bearing friction has been insignificant in the 3-in. version, but a full size unit would require larger bearings that would most certainly produce more heat.

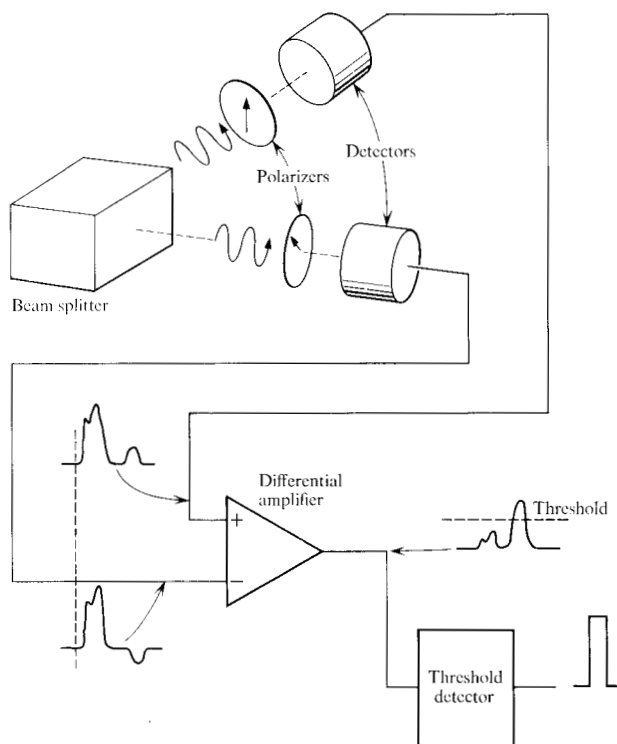
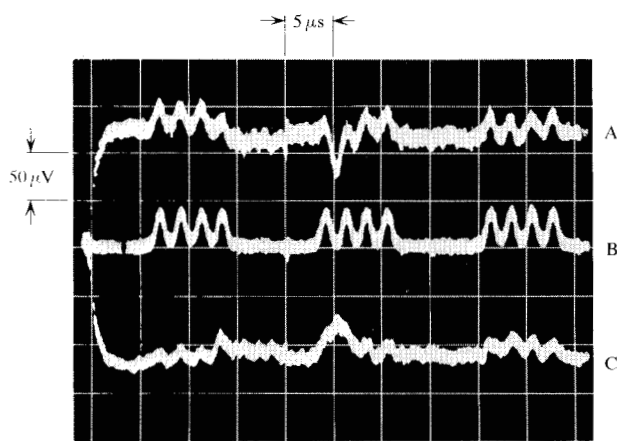


Figure 8 Differential detector arrangement used for canceling signal variation due to medium inhomogeneity. Polarizers are set at opposite sides of null.

Figure 9 Signal summation waveforms and recovered data. Traces A and C are the amplified output of the individual channel detectors; trace B is the sum of A and C.



Bearing longevity has been a key question in a device such as this and tests are underway to verify the acceptable load life of such a system. To date the oldest set of bearings in use has 1500 hours of running time and shows no sign of degradation.

Signal detection

As described earlier, the light beam modulation caused by the film is a rotation of the plane of its linear polarization, which is converted to an amplitude variation. It was found nearly impossible to reduce film transmission variation to a level that would permit simple threshold detection. A differential scheme was thus devised, as shown in Fig. 8.

The exit beam from the disk chamber is made to fall on a beam splitter, which separates it into two beams 90° apart. Between the splitter and the detectors are two analyzers, so arranged that a rotation in polarization creates an increase in the light intensity to one and a decrease to the other. The detectors are PIN diodes, the outputs of which are connected to a differential amplifier. Since the output of the amplifier is equal to the sum of the inverses of the incoming signals, amplitude variations due to transmission variation are cancelled and rotational variations are doubled. A sample photograph of the signal from a marginal film is shown in Fig. 9, to illustrate the powerful nature of this signal recovery technique. For additional information on this technique, a detailed study is available [10].

Summary

The scheme described above circumvents many of the hazards in present-day technology by using a sealed system and eliminating major sources of wear such as the moving head carriage and the collision between head and disk. Further, by employing low-mass optical elements for track addressing there is no need to move the large mass of an actuator and transducer assembly from track to track, and the attendant delay of >50 ms is thus eliminated. Finally, the possibility exists in this device of using multiple write/read stations, since their cost in the new technology can be made low enough to justify such a design. Half-latency time, which is due to rotational delay, can be considerably reduced if the system is capable of multiple access to a given track during a single revolution.

Although inductive recording technology has not yet reached its theoretical limits of density, this technique provides at least an order-of-magnitude improvement in areal density over the best projected inductive technique. To date, bits as small as $5 \times 8 \mu\text{m}$ have been recorded, and in principle it should be possible to further reduce spot size to about $1 \times 2 \mu\text{m}$. Only track servo problems then remain as a limiting factor in establishing maximum recording density perpendicular to the track. In conclusion, this technique represents a different approach to recording technology, the ultimate limits of which are determined by the wavelength of light, rather than by the signal-to-noise ratio and alignment limitations that now constrain the inductive techniques.

Acknowledgements

The author wishes to thank A. Juliana for construction of much of the system, and is indebted to D. Horne for the design and construction of much of the high-speed electronics required.

References

1. G. J. Fan and J. H. Greiner, *J. Appl. Phys.* **39**, 1216 (1968).
2. G. J. Fan and J. H. Greiner, *J. Appl. Phys.* **41**, 1401 (1970).
3. J. Marinace, "One Dimensional Laser Array for CW Operation at 77°K", *Abstract 85, Electrochemical Society Spring 1970 Meeting*.
4. B. R. Brown, *IBM J. Res. Develop.* **16**, 19 (1972).
5. Air Products Co., Allentown, Penna.; Cryogenic Technology, Inc., Waltham, Mass.; Malaker Corp., High Bridge, New Jersey.
6. K. Y. Ahn, *Appl. Phys. Letters* **17**, 347 (1970).
7. K. Lee and J. C. Suits, "Preparation of Doped EuO Films on Rotating Disks", presented at the *International Magnetism Conference (Intermag)*, Denver, Colorado, April 1971.
8. Barden Corp., Danbury, Conn., Data Sheet B3.
9. L. F. Mollenauer, C. D. Grandt, W. B. Grant and H. Panepucci, *RSI* **39**, 12, 1958 (1968).
10. R. H. Hunt, *IEEE Trans. Magnetics* **Mag-5**, 700 (1969).

Received July 16, 1971

The author is located at the IBM Research Laboratory, San Jose, California 95114.