

Electron Trapping Optical Data Storage System and Applications

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Abstract

A new technology developed at Optex Corporation out-performs all other existing data storage technologies. The Electron Trapping Optical Memory (ETOM™) media stores 14 gigabytes of uncompressed data on a single, double-sided 130mm disk with a data transfer rate of up to 120 megabits per second. The disk is removable, compact, lightweight, environmentally stable, and robust. Since the Write/Read/Erase (W/R/E) processes are carried out photonically; no heating of the recording media is required. Therefore, the storage media suffers no deleterious effects from repeated Write/Read/Erase cycling.

This rewritable data storage technology has been developed for use as a basis for numerous data storage products. Industries that can benefit from the ETOM data storage technologies include: satellite data and information systems, broadcasting, video distribution, image processing and enhancement, and telecommunications. Products developed for these industries are well suited for the demanding store-and-forward buffer systems, data storage, and digital video systems needed for these applications.

Electron Trapping Overview

The advent of digital information storage and retrieval has led to explosive growth in transmission, compression, and high capacity random access storage of data. A key limitation for growth of digitally based systems is the slow advance of erasable data storage technologies. New storage technologies are required that can provide higher data capacity and faster transfer rates in a more compact format. Magnetic disk/tape and current optical data storage technologies fail to provide all of the higher performance requirements of digital data applications.

The Electron Trapping Optical Memory (ETOM) Media developed at Optex Corporation out-performs all current data storage technologies. ETOM is a novel erasable data storage media which utilizes the phenomenon of electron trapping¹. Electron trapping is common in a class of luminescent materials known as IR stimuable phosphors. They are composed of a host lattice, typically an alkaline-earth sulfide, and two rare earth dopants (the luminescent and trapping centers). Data storage is a fully photonic process which involves the interaction of light with the dopant ions and their electrons within the media.

The Electron Trapping Optical Data Storage (ETODS) System uses two wavelengths of light to accomplish the Write/Read/Erase processes. The fundamental process responsible for the storage of data is the transfer of electrons between the two types of

dopant ions. The write/read/erase processes are fully reversible and occur at the atomic level within the crystal lattice structure.

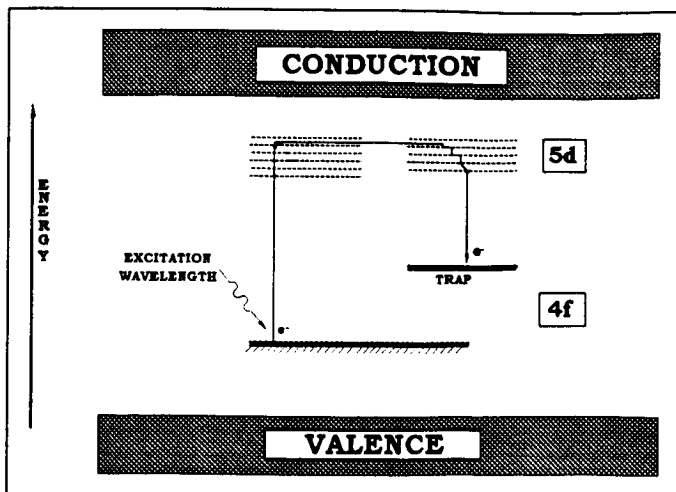


Figure 1a. Write operation

The **write** process involves raising an electron from the ground state of the luminescent ion to its excited state. This electron then migrates to a nearby trapping ion and falls to the ground state of that ion. Figure 1a illustrates the write process. It is important to note that the dopant ground and first excited states are within the bandgap of the host lattice. The ground states of both ions have a 4f configuration which is highly localized; therefore they are very stable. So, a trapped electron, barring excitation with

a stimulation source, will remain trapped indefinitely. The excited states of both ions have a 5d configuration and are much more extended. These extended orbitals overlap orbitals of nearby atoms in the lattice allowing for electron transfer through the lattice. The **read** process is the reverse of the write process; the only difference is the wavelength needed to detrapp the stored electrons. The trapped electron will remain trapped until a photon of the read light source excites it from the ground state to the excited state. From here it can migrate back to a luminescent ion and relaxes to the ground state. The transfer back to the ground state is accompanied by the emission of a photon which is detected by the electro-optical drive system and indicates stored data. Figure 1b illustrates this process. All traps need not be emptied in this process, thus allowing for multiple read passes prior to a refresh step. **Erasure** is carried out by simply increasing the Read laser power to completely detrapp all stored electrons.

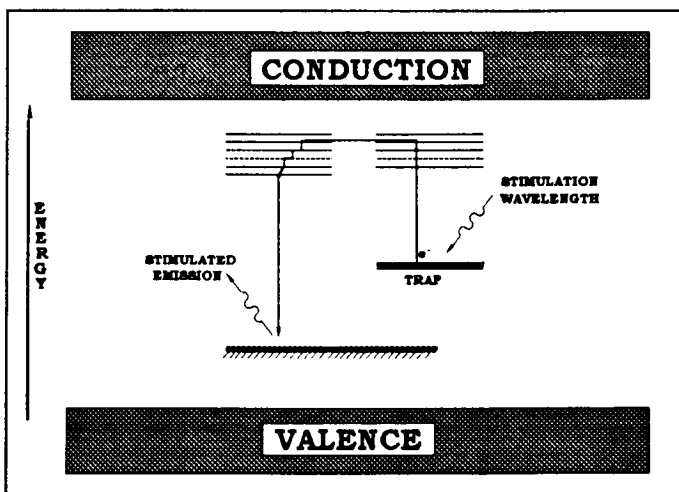


Figure 1b. Read/Erase Operation

Performance Features

The ETOM technology has many advantages over current erasable data storage technologies. Since the write/read/erase processes are carried out 100% photonically, no heating of the recording media is required. This provides a distinct improvement in media sensitivity and transition rates over current technologies. As a

result the media requires less energy to write a mark. A decrease in dwell time and/or laser power translates to higher data rates and decreased laser cost. The time to create a mark and read it back is also decreased since the write and read processes are photonic and not thermal.

ETOM media is also durable. It must be shielded from external light sources, so it is stored in a compact, light-tight cartridge. This forms a rugged package that easily can be removed from the drive. The media itself is environmentally stable as long as the proper stoichiometry is maintained during processing. Normal thermal fluctuations do not have an effect on the performance or stability of the media. In fact, the substrate and protective coatings would be destroyed prior to the loss of data. Thermal detrapping will occur only above 370 °C².

Analog performance

In a typical optical recording head, the optical stylus beam is formed using an objective lens with a Numerical Aperture (N.A.) of about 0.5. This lens forms a spot on the disk surface that is approximately 1.0 μm in diameter using conventional laser wavelengths. Within the media volume illuminated by the focused optical stylus beam, many dopant pairs will participate in the data storage process. The typical dopant pair density in an ETOM film is 10⁶ pairs/μm³ for a dopant concentration of 300 ppm. Therefore, there are approximately 10⁶ potential "traps" per cubic micron—the volume illuminated by the optical stylus beam. Essentially this corresponds to an effective domain of approximately 10⁻⁶ μm³. The number of traps filled during the write process depends on the field strength of the illumination and the absorption of the material. In this manner, the number of traps filled may be controlled by varying the intensity of the illuminating light.

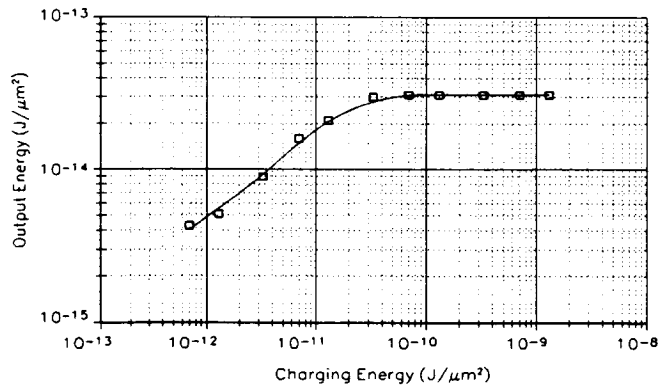


Figure 2. ETOM write saturation.

The linear response of ETOM material is illustrated in Figure 2. The graph shows emission energy (J/μm²) as a function of excitation (charging) energy (J/μm²) for a constant stimulation energy^[1]. The stimulation occurs at some time period after excitation is terminated. ETOM material illuminated by optical radiation at the excitation wavelength responds linearly over a broad region until a saturation level is reached. Saturation in this case is defined as maximum filling of available "traps".

For conventional two-state binary digital recording, the write energy is alternated between the region of no response and saturated response. It is the linear response

[1] The shape of the curve resembles the Hurter-Driffield, or DLog(E), curve for photographic film. In the case of the H-D curve, post-development film optical density is plotted as a function of exposure. Photographic film typically is characterized by a long linear portion of the curve where increased exposure results in increased density. At a point, called saturation, maximum density is achieved and further increases in exposure produce no further increase in film density.

region, however, that provides ETOM with its unique ability for analog signal recording. Although full analog recording is possible—we routinely demonstrate analog video recording on an ETOM disk—discrete multi-level recording provides many salient advantages. Discrete information coding provides greater noise immunity for a given band-limited data channel, and provides the opportunity to scale the information transfer rate while maintaining the integrity of source information.

Multi-level digital recording

Multi-level or non-binary digital recording^{3,4} takes advantage of the exceptionally wide dynamic range of ETOM media. This method of coding source information can provide up to four times the data capacity and transfer rate using four discrete amplitude levels. Multi-level recording is implemented by controlling the write laser illumination energy so that the number of filled traps in a data feature can be none, partial, or

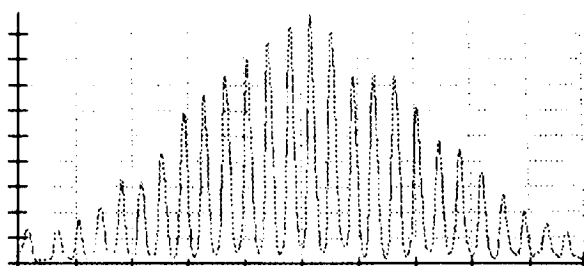


Figure 3. Recorded gray-scale.

complete. Figure 3 shows the result of recording a monotonically increasing and decreasing "gray" scale on an ETOM disk. The highest amplitude pulse represents the saturated recording level. Here thirteen discrete levels are shown. Several of the levels are not distinguishable due to non-uniformities in the coating of this particular sample. However, note that the pulse width remains uniform for all pulse amplitudes, illustrating the independence of pulse width and amplitude.

Pulse Amplitude Modulation (PAM) combined with Pulse Duration Modulation (PDM), or Pulse Position Modulation⁵ (PPM), provides a larger data channel symbol set for coding source information. In typical digital recording channels, information is carried in the phase of the recorded signal—either width or position of the pulses. Combining PAM and PDM—or PPM—creates a matrix arrangement of data channel symbols where information is carried in *both* the phase and the amplitude of the recorded signal. A simple MFM-type code provides a good example. In Modified-Frequency-Mark (MFM) coding there are three possible phase symbols—1.0, 1.5, and 2.0 bit cells long⁶. The equivalent 4-level code provides four amplitude symbols and three phase symbols for a total of twelve (12) code symbols. (One of these symbols—the "0"—is redundant so that there are only eleven usable symbols.) This yields more than three times as many usable symbols for the same physical mark dimension. Although this is a very simple explanation of a simple code system, it is evident that there is a significant capacity and data rate enhancement through the use of such coding.

Using a 4-level coding system, it is possible to enhance the capacity—the average number of source bits per recorded feature—by up to four times. Since the average number of bits per feature is increased, the average number of bits per second also is increased by the same factor if the number of features/second—the "mark" rate—is unchanged. This leads to a 4× increase in user data transfer rate.

When data is read out from the ETOM disk, the filled-trap density decreases proportionally with the intensity of the read-laser illumination. Therefore, it is possible to fully erase, or to partially erase, the data while reading. In the case of partial erasure, the various amplitude symbols decrease proportionally. After several read steps—depending on the intensity of the read illumination—the number of stored

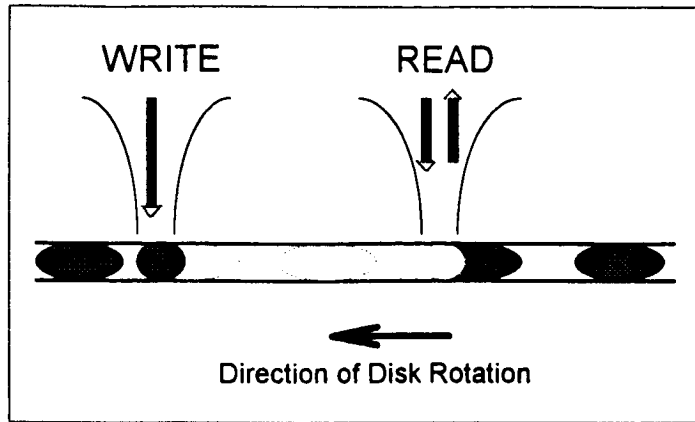


Figure 4. Refresh operation

electrons will fall below a critical detection threshold. At this point data is lost. In ETOM technology the data must be refreshed to retain information integrity. This refresh step is simply a read step followed with a restoring write step which can be performed automatically. Since the ETOM-based optical system contains the two laser beams—one for the write wavelength and one for the read

wavelength—no additional optics are required for the refresh operation. Figure 4 illustrates the optical stylus arrangement for a data refresh operation.

Using quaternary coding it is possible to store 14 gigabytes of data on a double-sided 130mm substrate with a transfer rate of 120 megabits per second. This capacity and transfer rate coupled with the features of erasability and random access forms a very versatile data storage system.

Applications

The ETOM media is capable of both analog and digital recording. An ETODS system with its massive data capacity, high transfer rate, and its ability to directly access random data fits a number of video and data storage applications. Industries that can benefit from the ETOM data storage technologies include: satellite data and information systems, broadcasting and video distribution, telecommunications, and computer data storage.

Satellite Data and Information Systems

ETOM-based products are ideally suited to the huge data requirements of imaging applications. An ETODS store-and-forward downlink system can be used to acquire and re-transmit data from satellites. There is a continuing pressure to increase the number of on-board information generating devices and to increase the resolution of the images collected. A higher capacity system with a greater transfer rate is needed.

The data collected during a single orbit of a polar orbiting satellite, for example, must be dumped in 10 minutes as the satellite travels from horizon to horizon. Faster transfer to the ground station would make it possible to collect more data per pass. Currently, the satellite dumps approximately 9 gigabytes of data for a single pass at a rate of 2.66 megabytes/sec⁷. A single 130 mm ETOM substrate could store this

amount of data with 5 gigabytes to accommodate future growth. The ETOM-based system could accommodate this data rate and volume with the added benefit of random access to any bit of data.

While the initial application of an ETODS system would most likely be a store-and-forward system at a ground-based downlink site, it might also find use in on-board satellite operations. The system would weigh less than current tape systems and contribute no additional EMI. Since the detrapping process is not temperature sensitive, operation at the temperatures encountered in space flight should be possible.

Broadcasting and Video Distribution

A digital video recorder based on ETOM materials holds particular promise for this industry. An ETODS system could store many hours of video on a single substrate with random access to any segment. This capability is unmatched in the industry and makes possible a variety of video applications that have simply not been practical without ETOM.

Today the broadcasting and video distribution industries are faced with technological advances that require high speed and high capacity storage devices. The switch from analog to digital signals and new products such as HDTV will virtually obsolete existing video tape storage products. An ETOM-based digital video recording system would complement many of these new technologies and will create many new applications in the video/broadcasting marketplace.

Video Buffering

An ETOM-based digital video recording system developed for TV cable system "head ends" would both simplify downloading of satellite signals and insertion of local commercials prior to re-transmission to subscribers. Cable operators could use this system to manipulate the hundreds of channels of digitally compressed programming that will be available in the near future.

An ETODS system is quite attractive in this application. A digital video recording system based on 4x subcarrier sampling of standard NTSC composite color video (i.e., the D-2 standard) requires approximately 1 GB per minute of digitized video frames, and a transfer rate of 120 Mb per second. A 130 mm ETOM disk could store 14 minutes without compression and offers 50 ms access time to any frame. With a data compression technique such as the proposed MPEG-2 standard, the same disk could store 18 hours of compressed digital video programming.

Video Post-Production

A digital video recording system for post-production editing would offer random access editing of digital video at much higher speeds than existing serial access tape machines and at far less cost than the usual tape-based products (e.g. D-1 and D-2 machines).

Video Distribution

A digital video recording system integrated into a conventional in-home cable TV converter box would enable the delivery of true "Video-On-Demand," because it would allow the consumer complete control over the time of viewing. The lack of true Video-On-Demand is widely believed by many industry experts to be the primary reason for the slow acceptance of Pay-Per-View programming. Hours of digitally compressed programming could be downloaded in minutes via cable, fiber optic, or Direct Broad-

cast Satellite (DBS). Consumers would then have the in-home convenience of Pay-Per-View combined with the breadth of selection and control of viewing time offered by video tape rental. Moreover, with adequate auditing and reporting safeguards built into the ETOM-based system, motion picture producers could offer first-run movies directly to the home viewing audience.

Consumer Products

A merger of the television and the computer is expected during the next decade. Consumer products based on the ETOM technology could also store video games and interactive video and multimedia applications.

Telecommunications

The merger of television and the computer and the linking of homes and offices using high performance optical fibers will create opportunities for ETOM-based systems in telecommunications. An example is the potential early use of ETOM-based buffer storage units in fiber optic systems. Increased capacity buffer storage will be important when data is downloaded from very high capacity "trunk" lines for regional and local distribution of data.

Computer Data Storage

While advanced digital video recording offers an excellent near-term opportunity for the commercial introduction of ETOM-based products, the computer data storage industry is perhaps the largest market in which ETOM technology could have an impact. ETOM's data density, data transfer rate, and potentially low cost, would make ETOM-based products attractive to a broad range of current computer users. Today's computer systems are becoming more and more sophisticated, yet their performance is often peripheral-limited. Although there are many different data storage devices (tape, optical, magnetic "hard" drives) that *partially* meet a computer user's needs (random access, removability, cost, performance, etc.) not a single one of them meets all his needs. ETOM technology allows for the development of products which meet all of the user's critical needs.

Summary

Perhaps the largest impact that ETOM-based products would have on technology stems from the fact that it is a truly photonic technology. Light is simply a better messenger than electricity. Optical fiber can carry far more information than traditional cable. Computer logic devices based on photonic processes are under investigation to make computers operate faster. Optical video and data storage as well can now benefit from the application of photonics.

Because of its high performance, an ETODS system would provide the data storage break-through needed for satellite data and information systems, broadcasting and video distribution, telecommunications, and computer data storage.

References

1. D. T. Brower and R. E. Revay, "Tuning of read/write/erase processes in Electron Trapping Optical Memory media," *Optical Data Storage '92, Proceedings of the SPIE*, ed. D. B. Carlin and D. B. Kay, vol. **1663**, pp. 86-91, Feb. 1992.
2. Urbach, F., Preparation and Characterization of solid luminescent materials, ed. Fonda and Seitz, John Wiley, Chap. 6, pp. 115-140, 1948.
3. A. M. Earman, "Optical data storage with electron trapping materials using M-ary data channel coding," *Optical Data Storage '92, Proceedings of the SPIE*, ed. D. B. Carlin and D. B. Kay, vol. **1663**, pp. 92-103, 1992.
4. T. Kasami, T. Takata, T. Fujiwara, and S. Lin, "On Multilevel Block Modulation Codes," *IEEE Transactions On Information Theory*, vol. **37**, no. 4, pp. 965-75, July 1991.
5. M. Ozaki, T. Furukawa, K. Tanaka, and T. Kubo, "An Effective Reproducing Method on Digital Optical Disk," *6th Conference on Video, Audio, and Data Recording*, pp. 105-11, 1986.
6. H. Kobayashi, "A Survey of Coding Schemes for Transmission or Recording of Digital Data," *IEEE Transactions On Communications Technology*, vol. COM-19, no. 6, pp. 1087-1100, Dec. 1971.
7. Personal conversation with R.L. Brower, July 2, 1992.

Panel Discussion on Magnetic/Optical Recording Technologies

Dr. P C Hariharan of Hughes STX was Moderator of a Panel Discussion on Magnetic/Optical Recording Technologies held September 23, 1992, at the Goddard Space Flight Center in Greenbelt, Maryland.

Members of Dr. Hariharan's panel were

Mr. Martin Clemow, Penny & Giles Data Systems, Inc.
Dr. Jean-Marc Coutellier, Thomson CSF / Laboratoire Central de Recherches
Mr. Bruce Peters, Datatape Inc.
Dr. Dennis Speliotis, Advanced Development Corporation
Mr. John W. Corcoran, Corcoran Associates
Mr. Allen Earman, OPTEX Corporation
Mr. William Oakley, Lasertape Inc.
Mr. Andrew Ruddick, ICI Imagedata
Dr. Yuan-Sheng Tyan, Eastman Kodak Co.

DR. HARIHARAN: Allen Earman is Manager of Systems Development Engineering at the Optex Corporation and got his MS in optics from the University of Rochester and BS in electrical engineering from the Virginia Polytechnic Institute and State University. He has worked in the field of optical recording for over 16 years and has presented four technical papers on the subject, most recently one titled, "Optical Data Storage with Electron Trapping Materials Using M-ary data channel coding." He has one use patent and another pending and has cochaired two optical data storage conferences. Mr. Earman is a member of SPIE and the IEEE LEOS, Magnetics and Information Theory Societies.

John Corcoran received the bachelor of electrical engineering degree from the Manhattan College and the master of electrical engineering from the Polytechnic Institute of Brooklyn. He migrated to California to work with Beckman and Whitley on high-speed photography. Subsequently, he worked on optical recording in the Advanced Technology Division of Ampex and was then converted to magnetic [inaudible]. He retired last year but keeps occupied on questions of archival storage, error characteristics, etc.

The remaining participants have already been introduced when they presented their papers.

I had hoped that I would be able to put up a chart from a paper that Mark Kryder was invited to write in 1989 in which he was asked to make some prognostications. But those of you who heard his paper earlier this morning will know what has been achieved by this year; and, if you had read his 1989 paper, you will also know that most of those achievements were expected by the year 2000, and not by the year 1992. So, one of the things that I would like to do in the discussions today is for the panel assembled here to state what they think the technology is capable of doing in the next 5 years, or may be the next 10 years. Mark has already given us his views. And in a couple of years, we'll have most of these people back, including Mark, and we'll ask them to sit back and tell us whether their predictions are on course, ahead or behind, and why.

capacity, data rate, generally getting much better performance from the available media in the immediate future. I don't see any reason why that should change as things go on. *I think Dennis is quite correct: any predictions we make are going to be short of what will actually really happen.*

MR. RUDDICK: I think there's another dimension to this issue and one that sometimes — I won't say it's forgotten about -- but we've heard a lot earlier on about some of the fundamental limitations of the technology, and I could prepare slides showing the fundamental limitations of optical technology as it applies to laser wavelengths, et cetera, et cetera.

The other important dimension that I think is important, however, is some of the engineering issues that need to be also considered to turn the fundamental limitations into real products. For example, some of the issues around substrate performance are going to be critical if any of these fundamental magnetic limitations are going to be achieved. I think that broadens the debate away from, if you like, the physics and the chemistry to some of the real practical engineering tasks associated with turning bright ideas into real products that are going to solve the data storage problems that we've heard about. And that makes predictions even more difficult because, it's easy to predict in some ways about the physics and the chemistry. It's not quite so easy to predict, for example, what laser powers are going to be available in five years' time, prices that are going to be appropriate for optical data storage. It's not easy to predict, for example, what the quality of substrates is going to be like in five years' time for the demands that these high-density storage systems are going to place. So, I think that's one comment I'd like to make.

DR. COUPELLIER: In my case, I have a double difficulty in answering that question, since we are dealing with both magnetics and optics in our system. In fact, it is a major advantage, for the following reasons. The density of information which can be recorded on tape is currently limited to 1 square micron per bit. The longitudinal resolution of the magnetic head is much better than that of conventional optics. In the latter case, it is limited by light diffraction phenomena. In the new Kerr readout component which I presented this afternoon, the longitudinal resolution is given by the width of the non-magnetic gap located between the two magnetic poles, as it is for a conventional inductive readout head. An optical head provides much higher transverse resolution. As a matter of fact, the magneto-optical layer constituting our Kerr transducer is continuous all along the tape width, the transverse resolution is then limited by the laser light diffraction phenomena. So, for both longitudinal and transverse resolutions, we use the best of magnetics and optics. This is one of the major advantages of the new recording system. The recording density is limited only by the tape pigment and coating.

MR. OAKLEY: I have three comments. The first one is a shootout between optical and magnetic. I don't believe laser power to be a limiting factor. The reason for that is that just within the infrared laser diode domain, it has already been demonstrated that by putting a small crystal amplifier in the laser cavity, the single-mode laser powers can be raised to approximately 10 watts. And that takes the data rates to terabytes per second. The cost is minimal. If you're talking about shorter wavelengths, then the doubling efficiency is approaching 50 percent, so several watts in the ultraviolet is probably possible within a few years.

To address the issue of ultimate capacities, I'd like to point out that all we've discussed today, except for Optex, is a spatial limitation to storage. Within the optical domain, you have another dimension you can use, which is the actual color of the laser itself. In the research labs, people have demonstrated spectral hole-burning techniques whereby shifting the laser wavelength very slightly allows a second bit to be recorded in the same location. Theoretically, this will allow something like 10,000 bits to be stored in each square micron of media, optically. And that raises the capacity of optical storage to whatever the number is. It's some horrendous number. So, the spectral modulation is a dimension that no one's even considered yet, in terms of limitations. Thirdly, in terms of technology change, the rapid technology change, I think we can solve that by just invoking the present financial, fiscal environment, which will limit technology change by rationing investment. So the technology can be very stable there for a long time.

MR. PETERS: I might offer a slightly different perspective, that is, I think that regardless of what technology or product implementation you're talking about, we're going to be hard pressed to keep up with the demand. If you look at what's happening in our ability to collect data, as well as our appetite to process it, we're going to really have to hustle on all fronts to keep up with it. And I dare say that in five years, users will still be complaining about data overload. With respect to magnetics, I would say that we're not limited by technology, but only in implementation, and there too only in the short term. Implementations will be driven by economics and our ability to deliver real, useful products. But there always seems to be that engineer who has a different approach that is very viable right around the corner to solve a particular implementation problem that we have. So, with respect to magnetics, I would say that we're still seeing very real potential for orders of magnitude areal density improvements and other factors that you would normally associate with them.

MR. EARMAN: Every couple of years or so, we try to take a measure of what we think the predicted improvements are going to be over the next couple of years. Maybe we do this every year now. But every time we do that, we overlook things that change very rapidly or new discoveries that happen from time to time. For example, just two years ago people were wishing short-wavelength lasers were available that could increase the capacity of a disk by four times or maybe six times or whatever. The recent work in blue and green lasers has been extremely exciting and extremely fast-changing. Also, in the spatial domain, we mentioned earlier, we can determine fundamental imaging limits based on wavelengths and the numerical aperture of the lens. However, AT&T's recent announcement of the stretched fiber end introduces a whole new field of investigation in that area. With the end of the fiber and using near-field rather than a far-field imaging, the capacity again goes up by a factor of perhaps three orders of magnitude. As my colleague also mentioned, about the multispectral recording, and as we talked about earlier, non-binary recording, all contribute to greater capacities and this is in leaps and bounds, not just gradual changes. So, trying to put an expectation on where we're going in the next five to eight years, or by the turn of the century, gets harder and harder, and makes more fools of the predictors.

DR. TYAN: I guess I'm chicken. I'm supposed to be on the optical side. But I would say that magnetics is probably going to be here forever. Optical is never going to replace magnetics totally. But I think we have learned in the past two days that the storage industry has become more and more diversified. And people are not going to judge the technology in the future just based on capacity. Maybe people will not be satisfied with 2000 hours of head life, or 2000 passes of tape life. And other kinds of considerations will become very important. So I think in terms of the future, there will be a need for both optical and magnetic. Just a matter of which technology will be the best for a particular application.

MR. CORCORAN: It's kind of awkward to be "tail-end Charlie" in such a distinguished group. I'll make a couple of comments, though. I've watched over the years the projections of resolution limits in optics and magnetics move slowly upward, and it never seems to stop. There's increasing sizes of memory required and there's the question increasing costs. The cost of memory itself has declined enough so we can keep expanding memory. I think the harder thing I see is how can we control the costs of the equipment that we're going to build so that America can produce things that will sell in a world market. In some ways I think that that's perhaps a worse challenge than anything we can do to increase the size of memories.

DR. HARIHARAN: Are there any comments or questions from the audience? Yes?

PARTICIPANT: [inaudible]

DR. HARIHARAN: Atomic force microscopy?

PARTICIPANT: Where does that technology go, and who will take advantage of it -- the magnetic guys or the optical guys?

DR. HARIHARAN: Well, Mark has a comment on that.

DR MARK KRYDER (Carnegie Mellon University, and Session Chair): I can make a comment on that. The problem with that technology is basically the same one that is faced by the AT&T/Bell Labs experiment that I was talking about earlier. All of them rely on gates of electric transducers and basically IBM's present, published best values is 100 KHz in a case where they were actually moving the field emission tip relative to the recording medium. They project that they might be able to get it up into the megabit or maybe, even a few megabits, per second. But that's about as far as they can go. So there is a real limitation with regard to moving the atoms around on the surface as to what sort of data rate they can get out of a system that does that. I think that's the obstacle there, and that's why I suggested this morning, with the near-field optical scheme, that the preferred approach is to use a flying head to make it look like a disk again, and so forth.

DR. HARIHARAN: Dennis, do you have a comment?

DR. SPELIOTIS: Not specifically for that, but if you consider electron beams, which is a technology that was not mentioned here, diffraction limits go down by four or five orders of magnitude. You have interactions that are unimaginable in the optical field; electron beams interact with anything. Deflection is trivial -- maybe too easy. You have everything, except that you need a vacuum and nobody's pursuing it. There's another dimension that we did not even discuss at all.

DR. HARIHARAN: You did work in electron beam technology, didn't you?

DR. SPELIOTIS: Right.

DR. HARIHARAN: We don't have the holographic memory people here either. There's an outfit in Texas that has been working on this for quite a while. Does any other member of the panel have a comment on this?

MR. CORCORAN: I could comment that between 1960 and 1973, Ampex built about six different electron beam recorders for various analog situations. And they achieved up to 100 MHz analog bandwidth, but there doesn't seem to be any real market. I think we're going to go more digital. We won't go holographic.

DR. HARIHARAN: I saw another hand raised over the back. No? If not, we'll go to a point that Dennis raised while the optical people were giving their talk. It is remarkable that there seems to be no activity from the Japanese on optical tape. Do you wish to comment on that, Dennis?

DR. SPELIOTIS: To me, it's remarkable, because a couple of years ago (I don't know exactly what the situation is now in Japan) there were over 100 companies or laboratories in Japan pursuing magneto-optics, mostly on rigid disk formats, for the development of materials for magneto-optics. Over 100 companies! And in the U.S., hardly anybody--only two or three companies. With that tremendous Japanese involvement in magneto-optics, there is hardly anything on optical tape. It is strange and I don't know if anybody has any insight into that.

MR. RUDDICK: I don't know whether it's great insight or not. We spent some time looking at magneto-optic tape as a technology in terms of feasibility and, I think, have concluded that the lifetime issues are such that it probably isn't a viable way to go. The corrosion characteristics of those materials tend to be very rapid and in the context of a rigid disk, which you conceal and enclose, it's a manageable issue. In the context of an open-reel tape or cartridge tape with a very thin protective coating perhaps, it seems much more of an issue, and my judgment is that wouldn't be the way you would go if you were developing an erasable optical tape product. On the more general comment about the fact that there is no optical tape activity in Japan, our information suggest that isn't strictly true and that there are some companies who are active. But they are promoting their activities toward consumer applications for high-definition digital TV. I'm sure we'll hear more about that in the next few years.

PARTICIPANT: Anybody out there putting optical tape in a cassette format?

DR. HARIHARAN: Bill Oakley has tried using it in a 3480 cartridge and you want to know whether it'll be in a two-reel cassette?

PARTICIPANT: Yes.

DR. HARIHARAN: Fine.

MR. RUDDICK: Yes, there are people working on that problem, and we are working with a number of companies who are looking at that issue. We can't talk about it, because it's not public, but there are activities.

MR. OAKLEY: I'd like to comment from the systems standpoint, which is that when you're talking about putting 100, perhaps 500 gigabytes of data in a single cartridge, you have all your eggs in one basket. In a multiuser environment, that is completely ludicrous. It may well be that we'll end up with both single-user, very large systems like CREO and also multi-user systems with a wall of small drives with only 10 gigabytes per cartridge, you know, in a microcartridge. So it'll go in both directions.

DR. HARIHARAN: Do you have a question?

DR. SPELIOTIS: One of the issues that Hari raised is that it seems like the pace of technology is accelerating, and the product cycles become shorter and shorter. A question: Why is that happening? What is driving it? Is the demand in the data storage or other applications requiring this kind of fast pace? Is it the threat of other technologies that pushes some of the technologies to advance faster? What are the reasons behind this, because it seems to be getting to a pace where the economics will not be there to sustain this growth. I mean, if the product cycles are so short, people will not be deriving the revenue out of these product developments to sustain further growth, so we're going to sort of commit suicide eventually. So, why are we doing this? What is driving us? Can there be some order and logic in this kind of pace? I'm puzzled by it, and I don't have an answer. Maybe some people have opinions about this.

DR. HARIHARAN: Linda?

MS. LINDA KEMPSTER (Strategic Management Resources): I think that's what's happening. Speaking as President of the local chapter of the Association for Information and Image Management, and I have 800 people in my chapter, the world I address is a paper management world. I have a person who is in my chapter that measures the number of documents by Washington Monuments. OK? It's sort of like the Library of Congress. She said, "I have 2 1/2 Washington Monuments full of paper." This person will never come out with an RFP to go on optical disk. The cost—I mean, it would be the national treasury here. But when she finds out, and I've been educating them — on what kind of economics magnetics can bring, because the people with paper problems have never thought about putting paper solutions on magnetics — then they'll come out with that kind of requirement for systems that can be responded to by the high-density magnetic tape solutions. So what's happening is that the tape people, who have always addressed or found their home in instrumentation data problems, and solving those problems — are now being forced — not forced, but encouraged -- to look at other markets where we have tremendous paper repositories that are trying to get on something electronic. Those folks have bumped into a very expensive optical disk ceiling, and they're looking for other solutions, and I think that's what's going to drive your market. That's where your solutions with tape are going to go, and that solution is going to go from magnetic tape to optical tape, because they still want to have the archive ability and what they think of as nonerasability and so forth. So it's going to be the paper industry, the microfilm, the people that used to put all their stuff on microfilm. Those people are going to be driving your industry, and that's where your customer base is coming from. Any other questions?

DR. HARIHARAN: Yes, Bill.

MR CALLICOTT (NOAA): I don't think [inaudible]

DR. HARIHARAN: You're saying that data which is not online and which is so voluminous is useless?

MR CALLICOTT: That's correct.

DR. HARIHARAN: OK. Mark?

DR. KRYDER: I think that's exactly the right answer. Let me comment that every new PC has come out at that rate, in 18 months. And that's what's driving [the pace of development]. Every PC has to have a new disk drive in it. It has to have a higher capacity and so forth. So, very clearly, that's what's driving it. I don't think that's negative, though. If you want my opinion, as far as the U.S. is concerned, the truth is, the disk drive industry resides in the U.S., and that's the one that has the short cycle time. The one which hasn't had the short cycle time has been tape -- VHS and so forth. All those are offshore. If we allow these industries to have such a long product lifetime that it comes down to only cost of manufacturing, somehow the community in this room, the U.S. people, we don't do well in that. In innovating and bringing out new products quickly we are good -- in fact we've done well in the disk drive business.

DR. HARIHARAN: Any other comments? Yes, Dave?

DR DAVID ISAAC (MITRE): [inaudible] IBM disk drives [inaudible] to the capacities of individual disks. The driver there seems to be access times, rather than capacity. Will we reach a natural limit in terms of cartridge size?

DR. HARIHARAN: Excuse me, did everyone hear the question, or should I ask Dave Isaac to come to the front and repeat it? Dave?

DR DAVID ISAAC: Hari, the question I had for the panel. In my exposure to IBM disk drives over the past 5 or 10 years, I've seen the capacities of the individual disk drives remain around a couple of gigabytes rather than growing larger and larger because the platter sizes have dropped from 12 inches to 10 inches to 5 1/4 to 3 to 2. It keeps going down to offset the increase in areal density. And the prime mover there seems to be access times rather than capacity. So I was wondering if we see these capacities going up in tapes with the helical scans and the opticals and the potential there. Really, are we going to reach an actual limit in terms of cartridge size? Will the cartridges start getting smaller? Is there a natural limit in terms of how much data people want to handle in one chunk in tape, or is the application of tape so different from that of disk that it really doesn't apply?

DR. HARIHARAN: Well, we saw the Sony nontracking technology tape yesterday, which is less than the size of a credit card. Let me pass the microphone along to the other members here.

DR. SPELIOTIS: The Sony cartridge — the so-called SCOOPMAN is the size of a stamp. So it is getting very much smaller than previous cartridges, but the question is: does that help throughput? Probably not. There is a real problem, I think, in the tapes. As I see it, how do we combine the best features of helical scan, which is typically large-capacity and slow throughput rate and low cost for the data cartridges, with the 3490 technology, which is very high cost, very high throughput, but relatively low capacity. We need an imaginative solution that would combine these two. If we can get that, I think it will answer a critical need for the next few years for several applications.

MR. CLEWOW: I'd like to make two points here. One is, I think that the capacity per unit item — whatever it may be, cartridge, cassette — from the tape point of view, is going to be driven by the application. I think you alluded to the fact that there is a limit to the maximum size per unit that people require for their application. I think that will be the natural breakpoint, if you like, that we'll get to that limit and then people will want the size reduced. And that's where the second point I'd like to make comes in. Particularly with tape drives that involve heads, reel motors, all the rest of it. You've got a problem with the mechanics. And you'll be getting into

micromechanics, and that is yet another field to consider. It's an unknown one at the moment, certainly from my point of view. It's a whole new technology, and I think the limit on the size with tape cassettes, tape cartridges, will be determined by the mechanics of the situation. Again, you come down to a cost. You get into a whole new field. It's an unknown at the moment.

MR. RUDDICK: I guess my response is that's a very complicated equation, and I'm not sure I understand all the issues around it. But certainly, the granularity of the data is something that I think does have a definitive size, depending on the application and the system design. The 1-terabyte capacity tapes certainly have their niche and their application, and the 100-gigabyte, 50-gigabyte, 3480 cartridge similarly. And, as I said earlier, we also have development programs looking at smaller formats. And again I think those sizes with those capacities and that granularity, also have their applications in different systems. So I don't think I can give a simple answer to that question. It's very application-system-dependent.

DR. COUTELLIER: The amount of data that can be stored is proportional to the magnetic surface you have in your cassette. And one way of decreasing the access time would be to change the form factor of the cassette itself by using smaller tape lengths and higher widths. This raises the question of track-following on wider tapes. You will have to deal with shrinkage, temperature effects, things like that. What kind of track-following servo will be implemented on the system? It could be a mechanical adjustment of the head on the tape. It could also be, as we can do in our recorder, an electronic track-following system. We have indeed a very nice feature available: if the optics is made such that more than one CCD pixel is associated with each track, we get many samples per track. If we are able to recognize on which pixel a servo track is located, it is then possible to shift the samples electronically in registers, and dispense with mechanical adjustments.

DR. HARIHARAN: The Sony people have shown that you don't really need to track anymore.

DR. COUTELLIER: Yes, but then the helical track length has to be made short to reduce the number of bits which have to be stored before data recovery can be attempted. The tape width is reduced, so to compensate, it has to be made longer to store the large number of bits needed for computer backup, HDTV, etc. This raises the problem of access time once again.

DR. HARIHARAN: But the NT cassette is the size of a postage stamp; even though it is not being used for digital data storage now, it does hold 693 Mbytes of digital music, and thus exceeds in capacity the popular CD-ROM.

MR. OAKLEY: I'd like to answer a question that really wasn't asked but is fundamental to this. The question to ask was posed in terms of latency for disks. I'd like to point out that the intent of the MCC program in Austin, Texas, is to replace disks. That's a crystal holographic system, and their intent there is to have a 10-gigabyte secondary memory with latency of less than 1 microsecond. So the hierarchy of a future system, consists of CPU, and a holographic crystal memory. And that crystal memory is supported by a tape system. So the real question is, How big is your holographic memory, and what is the cycle time on that? It seems to me if you have a 10-gigabyte holographic memory, what you need to do is load data sets, 10-gigabyte sized, to that every few seconds. So tape array's the answer to that, with maybe 10 seconds access time on the tape array. That's a prediction, by the way, about the demise of disk drives for large systems.

MR. PETERS: My comment is really a follow-on to a comment that was just made. I think we're going to see new things in the future, just like we've done in the past and maybe at an increasing rate. One of the things we will see is well-packaged, hybrid storage subsystems that actually are combinations of the various technologies and media for specific applications.

MR. EARMAN: The tape-based systems, unlike the disk-based systems - well, actually even the disk-based systems to a certain point - are really application driven. And depending on which application you're using determines the size of the acceptable amount of data that can be stored. The example that Bill mentioned earlier was that of 500 gigabytes on a single cartridge

on a multiuser system. It would be potentially catastrophic because of the loss of information if something happened to that one drive or that one cartridge. We also can draw an analogy to the consumer video system, such as the VHS and Beta systems. The original concept behind the VHS cartridge was to get 2 hours of video on a single cartridge because that would cover most movies that were available. So, you could store a single movie on a single tape. And of course with the 3X increase in capacity by going to the slower speed, you were able to get up to 6 hours, or 3 movies, on the tape. There hasn't been a lot of drive to push the capacity much beyond that, because if you could possibly put 18 movies or something like that, on a single tape, the loss of that tape would be catastrophic to your movie library, whereas a loss of 1 to 3 movies is not so significant. And that same idea, of a minimum volume and a maximum volume, also came along with the D2 systems. The medium cassette for the D2-based digital video contains about 94 minutes of capacity in digitized, full-rate (i.e., not compressed) video. Again, that was driven by having a minimum of 90 minutes on a single cartridge, even though that D2 cartridge is physically larger than the VHS cartridge.

DR. TYAN: Maybe just a follow-on to your comment here. When the technology becomes available that you can do more, you can store more. You can generate new applications, too. For example, in video cassette, people are working on tapes which can store HDTV; it requires the storage of much more information. Another example is for document storage. I think it goes both ways.

MR. CORCORAN: In my mind, the size of the file and the access times are inherently linked. You don't want to make a file too big or you just make your ability to find an item very difficult. It's all right in the TV system -- we have a D2 cassette, which I believe holds 3 hours. And it's quite large. But they are putting them in some storage systems. I kind of think it's monstrous. It's much better to handle a block of perhaps 26 gigabytes, which is the small cassette in the same class. It's a more convenient package for the storage of data.

DR. HARIHARAN: Let me ask another question here. The issue of VHS was brought up. VHS was a competitor to the Beta format introduced by Sony. Is there some such competition going on which has caused the displacement of D1 by D2 and of D2 by D3? Will the use of these technologies for data storage result in some of us being left with unsupported or unsupported hardware and/or format?

MR. EARMAN: I'll make a comment on that. I'm not very familiar with the D3 configuration, but regarding the D2 and the D1, right now, they're used for quite different purposes. The D2 is based mainly on composite video, and the D1, on component video. For general purpose usage, the D2 composite video is sufficient. But for most production houses, where television, commercials, whatever, especially with a lot of computer-animated artwork, is being done, component video is really gaining ground over composite video. There's more of a desire to have D1 systems in those setups. So there's still quite a bit of competition for different purposes and different uses between D1 and D2.

DR. HARIHARAN: Larry Lueck has recently predicted that magnetic recording is a dying duck. Now you are saying that D1, in particular, is not a dying duck and it's not a dead duck. That right? Allen?

MR. EARMAN: No, not in the near future.

DR. SPELIOTIS: The question I think is very interesting and I would like to see a show of hands: what is the opinion of the audience? Is magnetic recording going to die sometime soon and be replaced by a completely solid state, electronic type memory, or will it just keep growing and electronic buffers will coexist and support and extend its usefulness? What is the opinion of the audience? Because some people are predicting that we are in a dying industry and we're going to see in the very immediate future a decline in the volume and applications and revenues of this industry. Does anybody feel that the industry is threatened by solid state to the extent that it would go out of existence by the end of the decade or something like this?

MS LINDA KEMPSTER: I would think that the magnetic tape industry is going to die when every MIS data processing guy back in the lab, doing the same thing every day, dies.

MS LINDA KEMPSTER: I was introduced to optical disk in 1983-84. When I described optical disks to the MIS folks they said, "No way am I putting my data on that shiny blue disk, I've got my tapes." As long as you have a whole generation of those people, you will have a tape market. Maybe they'll change to optical disks in another generation down the line. As long as you've got some of those old tape dudes, you're going to have tapes. They're going to be around.

DR. SPELIOTIS: But there are a lot of new tape dudes coming along. So they'll never die.

MS LINDA KEMPSTER: This is true, as tape formats, capacities and applications expand, there will be *new* tape dudes and dudettes.

DR. HARIHARAN: Thanks. Pat [Mr Patric Savage of Shell] Would you like to make a comment along the lines of: We take care of our eggs by watching our baskets? Would you please come to the front so everyone can hear you?

MR SAVAGE (Shell): We do put all of our eggs in one basket, but we watch that basket!

MR. OAKLEY: Hari, when Pat gets done, I have a comment I'd like to make as well, about the massive upcoming proliferation of tape systems.

DR. HARIHARAN: OK.

MR SAVAGE: What was that last question? The problem that we have in our industry is exemplified by the scene that we have at Shell. Some handful of years ago, we converted to 3480. We didn't convert; we stopped using round tape and started using 3480. We now have about 900,000 3480 cartridges of permanent data. And we still have, unconverted, about 1 million round tapes of 6250 data. We have migrated all of our 1600 bpi stuff and all previous data, so we only have 6250 round tapes and 3480 right now. The problem that we have obviously is that migrating a million reels of round tape is an extremely expensive and long-enduring project. You simply can't do it overnight. It's labor-intensive. It's the kind of thing that you would like to be able to migrate now, and not have to do that again for another 30 years. On the other hand, if we were to migrate it to 3480 right now, we know the 3480 technology is already obsolescent as the 3490 technology takes over. We would be converting to something that, yes, exists now, but the data on those round tapes is not likely to be used very much during the lifetime of 3480 technology, so it would soon again have to be migrated. I'd like to put it in an icebox and sock it away for a long time. On the other hand, whatever I put it in, I want to be very, very sure that at the end of that archiving period or epoch, there are still drives around that I can read my data back with. Probably not much concerned with the retrieval data rate at that time, because we will probably copy it from the archive to the currently in-use medium. So, migrating to a new technology that probably will not last for more than 5 or 6 years is a very costly thing for me to be looking at. I would like to migrate to something that is as permanent as possible but with definite assurance that drive technology will be clearly available at the end of that archiving period. I would like to make another comment. I believe that what I heard here from the speakers and what I know of the MCC holographic storage in doped crystals are that these kinds of technologies could actually be brought into effective marketing position. I have enough vision to see that the MCC stuff, in principle, could literally take over everything that the rest of you guys are doing. That's all of the optical, all of the magnetic, and all of the magneto-optic. In principle, it could do that. It would take some money to make that happen. And it really could happen somewhere around the end of the decade.

DR. SPELIOTIS: But the idea has been around for 30 years, so what makes you think that it's going to happen by the end of the decade?

MR SAVAGE: I know. I've been tracking it myself for 30 years, Dennis. The difference is the clever little advances that have been made in the new ideas that MCC has brought into this area. My latest contact with them was about a year ago. I left believing that if they had enough money and had enough vision, that they could bring it to pass. It's got all the qualities that we really want for deep archiving -- high bandwidth, low cost, random access, all those good things.

DR. HARIHARAN: Infinite stability?

MR SAVAGE: Yes, infinite stability.

DR. HARIHARAN: Inexpensive too?

DR. SPELIOTIS: Motherhood.

MR SAVAGE: All those good things.

DR. HARIHARAN: You said you had a comment, Bill?

MR. OAKLEY: OK. I'd like to change the direction of the discussion slightly by pointing out that in the computer environment, historically we've seen diminishing interest in very large systems. Thirty, twenty, even ten years ago, we had one CPU serving thousands of users, and that system is rapidly disappearing with the advent of workstations and distributed computing. What we're talking about here today is massive data centers. The data being distributed over networks is very much like the old multiuser system, but it turns out that with the optical tape type technology, if you can get 100 gigabytes in a 3480 cartridge, you can replicate that quite cheaply. You can mail it across country overnight for a few dollars. And 100 gigabytes, by the way, is equivalent to 24 hours' continuous transmission on an Ethernet line. So perhaps the way of the future is not to have very large databases with massive fiber-optic, high-speed data nets but just to use a whole pile of FedEx envelopes and a stack of 3480 cartridges. Every user gets his own 200 or 300 gigabytes that he's interested in.

DR. HARIHARAN: Bill, my thesis advisor was a graduate student at Cambridge University in England, and he was one of the users of the very earliest computers called EDSAC -- Electronic Delay Storage Automatic Calculator, and the memory there was mercury delay lines. He used to tell me that if more than two people got into the computer room, the temperature went up sufficiently that the number of bits that could be stored in the delay line changed. Now, we already have 5 million miles of fiber in this country, I am told, and if we can put in another 50 million miles of fiber and we do get the gigabit network, in principle I can ask Sam Coleman to start pumping in the data at Lawrence Livermore and have regenerative repeaters here in Baltimore or Goddard and recirculate the thing and I can have a memory, of the grand-old type that they were using in the early machines, but with substantially higher capacities, available. Anybody connected to the network can capture the bits as they flow by. Maybe it's slow access.

MR. OAKLEY: I can't respond to that. What I had in mind was that with the rapid growth in workstations, if there would be a market developed in using optical tapes in workstations, then the cost of the 10-15-megabyte/second, 100-gigabyte, tape drive, in that kind of volume, is going to drop down to maybe \$1000 per tape drive. So that means the user with an autoloader, just 10 cartridges, each at a 100 gigabytes, is going to have, for maybe \$1500, a desktop terabyte system. And that will impact the use of networks.

DR. HARIHARAN: I'm sure that those things are going to occur, because workstations are getting more powerful and Andy Heller has threatened to unleash the Godbox -- giga everything on your and my desk--gabits, gigabytes, gigaflops, giga instructions per second. That should to come to pass. And he said it's possible within the next 3 years for a price of around \$30,000. There's going to be a lot of activity in, not just processing data, but in reprocessing data that we already have. I'm sure we'll find ways to put to use the new networks, the high-capacity links that we have, and we'll make pretty good use of those.

Introduction of Dr. Dennis Speliotis (After-Dinner Speaker)

DR HARIHARAN: Ladies and gentlemen, it is my pleasure to introduce Dr Dennis Speliotis as our after-dinner speaker. He was born in the Peloponnesus in Greece, but came to the US for his college education, obtaining his bachelor's and master's degrees in electrical engineering from the University of Rhode Island and the Massachusetts Institute of Technology, respectively, and his Ph.D. in solid state physics from the University of Minnesota. After graduation, he worked at IBM till 1967 before joining the University of Minnesota as Associate Professor. There he founded the Magnetics Research Laboratory. He then became a co-founder, director, vice president and general manager of Micro-Bit corporation. In 1967 he founded Advanced Development Corporation and continues as its president. He started Digital Measurement Systems in 1984, and has been able to sell the measuring equipment made there even to the Japanese.

Dr Speliotis is the author of over 150 technical papers, has been an IEEE Distinguished Lecturer, and has been an invited technical speaker at over 30 international conferences. He has also organized numerous conferences and symposia, and is as energetic and productive today as he was 30 years ago. In September this year, I had the privilege, along with a select group of others, to proceed on a pilgrimage in search of the elusive hexagonal Barium Ferrite platelets. Larry Lueck has captured the essence of the battle Dr Speliotis has been waging on behalf of this elixir of magnetic recording in the cover art of his MMIS Newsletter. Let me add that the First International Symposium on Barium Ferrite in Kalamata, Dr Speliotis' birthplace, was a great success, and brought together some of the keenest intellects at work in the field of magnetic recording.

Without further ado, let me present to you Dr Speliotis.