Optical Computing

1. Optical Components and Storage Systems

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Optics has been used in computing for a number of years but the main emphasis has been and continues to be to link portions of computers, for communications, or more intrinsically in devices that have some optical application or component (optical pattern recognition, etc). Optical digital computers are still some years away, however a number of devices that can ultimately lead to real optical computers have already been manufactured, including optical logic gates, optical switches, optical interconnections, and optical memory. The most likely near-term optical computer will really be a hybrid composed of traditional architectural design along with some portions that can perform some functional operations in optical mode.

Introduction

With today's growing dependence on computing technology, the need for high performance computers (HPC) has significantly increased. Many performance improvements in conventional computers are achieved by miniaturizing electronic components to very small micron-size scale so that electrons need to travel only short distances within a very short time. This approach relies on the steadily shrinking trace size on microchips (i.e., the size of elements that can be 'drawn' onto each chip). This has resulted in the development of Very Large Scale Integration (VLSI) technology with smaller device dimensions and greater complexity. The smallest dimensions of VLSI nowadays are about 0.08 mm. Despite the incredible progress in the development and refinement of the basic technologies over the past decade, there is growing concern that these technologies may not be capable of solving the computing problems of even the current millennium. Applications of HPC and visualization

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technologies lead to breakthroughs in engineering and manufacturing in a wide range of industries. With the help of virtual product design and development, costs can be reduced; hence looking for improved computing capabilities is desirable. Optical computing includes the optical calculation of transforms and optical pattern matching. Emerging technologies also make the optical storage of data a reality.

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The speed of computers was achieved by miniaturizing electronic components to a very small micron-size scale, but they are limited not only by the speed of electrons in matter (Einstein's principle that signals cannot propagate faster than the speed of light) but also by the increasing density of interconnections necessary to link the electronic gates on microchips. The optical computer comes as a solution of miniaturization problem. In an optical computer, electrons are replaced by photons, the subatomic bits of electromagnetic radiation that make up light. Optics, which is the science of light, is already used in computing, most often in the fiber-optic glass cables that currently transmit data on communication networks much faster than via traditional copper wires. Thus, optical signals might be the ticket for the fastest supercomputers ever. Compared to light, electronic signals in chips travel at snail speed. Moreover, there is no such thing as a short circuit with light, so beams could cross with no problem after being redirected by pinpoint-size mirrors in a switchboard. In a pursuit to probe into cutting-edge research areas, optical technology (optoelectronic, photonic devices) is one of the most promising, and may eventually lead to new computing applications as a consequence of faster processor speeds, as well as better connectivity and higher bandwidth.

The pressing need for optical technology stems from the fact that today's computers are limited by the time response of electronic circuits. A solid transmission medium limits both the speed and volume of signals, as well as building up heat that damages components. For example, a one-foot length of wire produces approximately one nanosecond (billionth of a second) of time delay. Extreme miniaturization of tiny electronic com-

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ponents also leads to 'cross-talk' – signal errors that affect the system's reliability. These and other obstacles have led scientists to seek answers in light itself. Light does not have the time response limitations of electronics, does not need insulators, and can even send dozens or hundreds of photon signal streams simultaneously using different color frequencies. Those are immune to electromagnetic interference, and free from electrical short circuits. They have low-loss transmission and provide large bandwidth; i.e. multiplexing capability, capable of communicating several channels in parallel without interference. They are capable of propagating signals within the same or adjacent fibers with essentially no interference or cross talk. They are compact, lightweight, and inexpensive to manufacture, as well as more facile with stored information than magnetic materials. By replacing electrons and wires with photons, fiber optics, crystals, thin films and mirrors, researchers are hoping to build a new generation of computers that work 100 million times faster than today's machines.

The fundamental issues associated with optical computing, its advantages over conventional (electronics-based) computing, current applications of optics in computers are discussed in this part. In the second part of this article the problems that remian to be overcome and current research will be discussed.

Background

Optical computing was a hot research area in the 1980s. But the work tapered off because of materials limitations that seemed to prevent optochips from getting small enough and cheap enough to be more than laboratory curiosities. Now, optical computers are back with advances in self-assembled conducting organic polymers that promise super-tiny all-optical chips [1]. Advances in optical storage device have generated the promise of efficient, compact and large-scale storage devices [2]. Another advantage of optical methods over electronic ones for computing is that parallel data processing can frequently be done much more easily and less expensively in optics than in electronics [3].

Parallelism, the capability to execute more than one operation simultaneously, is now common in electronic computer architectures. But, most electronic computers still execute instructions sequentially; parallelism with electronics remains sparsely used. Its first widespread appearance was in Cray supercomputers in the early 1980's when two processors were used in conjunction with one shared memory. Today, large supercomputers may utilize thousands of processors but communication overhead frequently results in reduced overall efficiency [4]. On the other hand for some applications in input-output (I/O), such as image processing, by using a simple optical design an array of pixels can be transferred simultaneously in parallel from one point to another.

Optical technology promises massive upgrades in the efficiency and speed of computers, as well as significant shrinkage in their size and cost. An optical desktop computer could be capable of processing data up to 100,000 times faster than current models because multiple operations can be performed simultaneously. Other advantages of optics include low manufacturing costs, immunity to electromagnetic interference, a tolerance for low-loss transmissions, freedom from short electrical circuits and the capability to supply large bandwidth and propagate signals within the same or adjacent fibers without interference. One oversimplified example may help to appreciate the difference between optical and electronic parallelism. Consider an imaging system with 1000×1000 independent points per mm^2 in the object plane which are connected optically by a lens to a corresponding number of points per mm^2 in the image plane; the lens effectively performs an FFT of the image plane in real time. For this to be accomplished electrically, a million operations are required.

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Parallelism, when associated with fast switching speeds, would result in staggering computational speeds. Assume, for example, there are only 100 million gates on a chip, much less than what was mentioned earlier (optical integration is still in its infancy compared to electronics). Further, conservatively assume that

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each gate operates with a switching time of only 1 nanosecond (organic optical switches can switch at sub-picosecond rates compared to maximum picosecond switching times for electronic switching). Such a system could perform more than 10^{17} bit operations per second. Compare this to the gigabits (10^9) or terabits (10^{12}) per second rates which electronics are either currently limited to, or hoping to achieve. In other words, a computation that might require one hundred thousand hours (more than 11 years) of a conventional computer time could require less than one hour by an optical one.

But building an optical computer will not be easy. A major challenge is finding materials that can be mass produced yet consume little power; for this reason, optical computers may not hit the consumer market for 10 to 15 years. Another of the typical problems optical computers have faced is that the digital optical devices have practical limits of eight to eleven bits of accuracy in basic operations due to, e.g., intensity fluctuations. Recent research has shown ways around this difficulty. Thus, for example, digital partitioning algorithms, that can break matrix-vector products into lower-accuracy sub-products, working in tandem with error-correction codes, can substantially improve the accuracy of optical computing operations. Nevertheless, many problems in developing appropriate materials and devices must be overcome before digital optical computers will be in widespread commercial use. In the near term, at least, optical computers will most likely be hybrid optical/electronic systems that use electronic circuits to preprocess input data for computation and to post-process output data for error correction before outputting the results. The promise of all-optical computing remains highly attractive, however, and the goal of developing optical computers continues to be a worthy one. Nevertheless, many scientists feel that an all-optical computer will not be the computer of the future; instead optoelectronic computers will rule where the advantages of both electronics and optics will be used. Optical computing can also be linked intrinsically to quantum computing. Each photon is a quantum

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of a wave function describing the whole function. It is now possible to control atoms by trapping single photons in small, superconducting cavities [5]. So photon quantum computing could become a future possibility.

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Some Key Optical Components for Computing

The major breakthroughs on optical computing have been centered on the development of micro-optic devices for data input. Conventional lasers are known as 'edge emitters' because their laser light comes out from the edges. Also, their laser cavities run horizontally along their length. A vertical cavity surface emitting laser (VCSEL – pronounced 'vixel'), however, gives out laser light from its surface and has a laser cavity that is vertical; hence the name. VCSEL is a semiconductor vertical cavity surface emitting microlaser diode that emits light in a cylindrical beam vertically from the surface of a fabricated wafer, and offers significant advantages when compared to the edge-emitting lasers currently used in the majority of fiber optic communications devices. They emit at 850 nm and have rather low thresholds (typically a few mA). They are very fast and can give mW of coupled power into a 50 micron core fiber and are extremely radiation hard. VCSELS can be tested at the wafer level (as opposed to edge emitting lasers which have to be cut and cleaved before they can be tested) and hence are relatively cheap. In fact, VCSELs can be fabricated efficiently on a 3-inch diameter wafer. A schematic of VCSEL is shown in *Figure* 1. The principles involved in the operation of a VCSEL are very similar to those of regular lasers. As shown in *Figure* 1, there are two special semiconductor materials sandwiching an active layer where all the action takes place. But rather than reflective ends, in a VCSEL there are several layers of partially reflective mirrors above and below the active layer. Layers of semiconductor with differing compositions create these mirrors, and each mirror reflects a narrow range of wavelengths back into the cavity in order to cause light emission at just one wavelength.

VCSEL is a semiconductor vertical cavity surface emitting microlaser diode that emits light in a cylindrical beam vertically from the surface of a fabricated wafer, and offers significant advantages when compared to the edge-emitting lasers currently used in the majority of fiber optic communications devices.

Spatial light modulators (SLMs) play an important role in

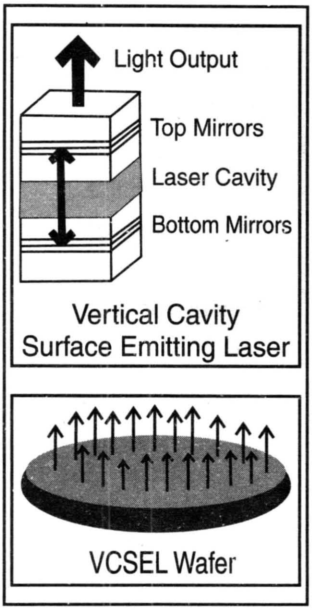

Figure 1. A schematic of the VCSEL and its possible miniaturization into wafer.

several technical areas where the control of light on a pixel-by-pixel basis is a key element, such as optical processing, for inputting information on light beams, and displays. For display purposes the desire is to have as many pixels as possible in as small and cheap a device as possible. For such purposes designing silicon chips for use as spatial light modulators has been effective. The basic idea is to have a set of memory cells laid out on a regular grid. These cells are electrically connected to metal mirrors, such that the voltage on the mirror depends on the value stored in the memory cell. A layer of optically active liquid crystal is sandwiched between this array of mirrors and a piece of glass with a conductive coating. The voltage between individual mirrors and the front electrode affects the optical activity of the liquid crystal in that neighborhood. Hence by being able to individually program the memory locations one can set up a pattern of optical activity in the liquid crystal layer. *Figure* 2(a) shows a reflective 256x256 pixel device based on SRAM technology. Several technologies have contributed to the development of SLMs. These include micro-electro-mechanical devices, such as, acousto-optic modulators (AOMs), and pixelated electro-optical devices, such as liquid-crystal modulators (LCMs). *Figure* 2(b) shows a simple AOM operation in deflecting light beam direction. Encompassed within these categories are amplitude-only, phase-only, or amplitude-phase modulators.

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Broadly speaking, an optical computer is a computer in which light is used somewhere. This can means fiber optical connections between electronic components, free space connections, or one in which light functions as a mechanism for storage of data, logic or arithmetic. Instead of electrons in silicon integrated circuits, the digital optical computers will be based on photons. Smart pixels, the union of optics and electronics, both expands the capabilities of electronic systems and enables optical systems with high levels of electronic signal processing. Thus, smart pixel systems add value to electronics through optical input/output and interconnection, and value is added to optical systems through electronic enhancements which include gain,

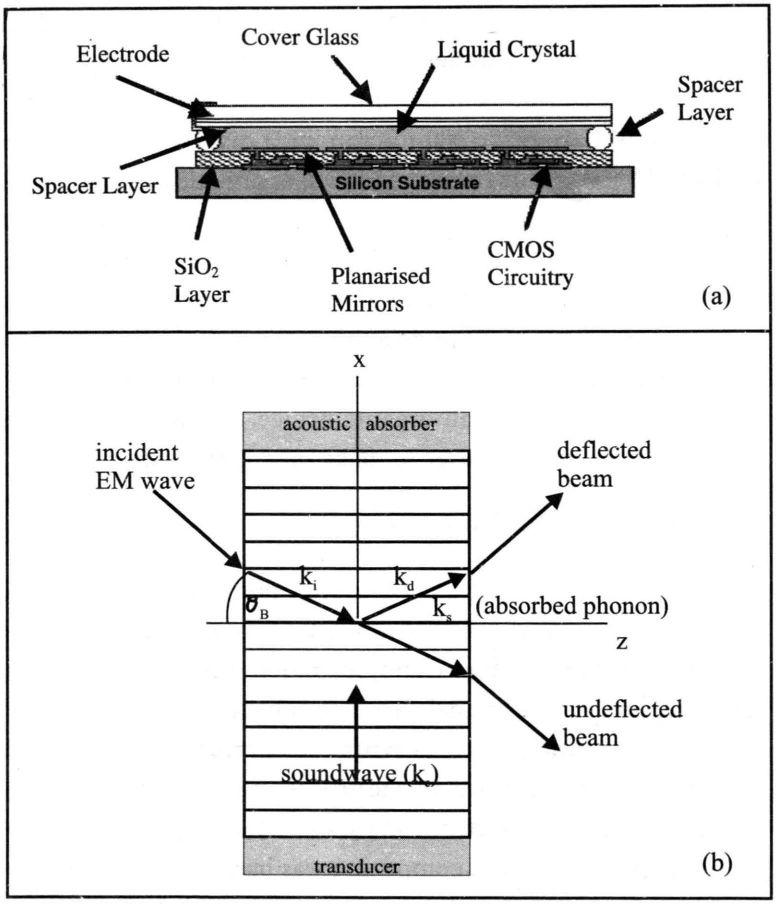

Figure 2. (a) A reflective 256x256 pixel device based on SRAM (Static Random Access Memory) technology with embedded CMOS (Complimentary Metal-Oxide Semiconductor).
(b) Schematic diagram of an Acousto-Optic Modulator (AOM) deflection principle.

feedback control, and image processing and compression. Smart pixel technology is a relatively new approach to integrating electronic circuitry and optoelectronic devices in a common framework. The purpose is to leverage the advantages of each individual technology and provide improved performance for specific applications. Here, the electronic circuitry provides complex functionality and programmability while the optoelectronic devices provide high-speed switching and compatibility with existing optical media. Arrays of these smart pixels leverage the parallelism of optics for interconnections as well as computation. A smart pixel device, a light emitting diode (LED) under the control of a field-effect transistor (FET), can now be made entirely out of organic materials on the same substrate for the first time. In general, the benefit of organic over conventional semiconductor electronics is that they should (when mass-production techniques take over) lead to cheaper, lighter, circuitry that can be printed rather than etched. Scientists at Bell Labs [6] have made 300-micron-wide pixels using polymer FETs and LEDs made from a sandwich of organic materials, one of which allows electrons to flow, another which acts as highway for holes (the absence of electrons); light is produced when electrons and holes meet. The pixels are quite potent, with a brightness of about 2300 candela/m^2, compared to a figure of 100 for present flat-panel displays [6]. A Cambridge University group has also made an all-organic device, not as bright as the Bell Labs version, but easier to make on a large scale [7].

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Uses of Optics in Computing

Currently, optics is used mostly to link portions of computers, or more intrinsically in devices that have some optical application or component. For example, much progress has been achieved, and optical signal processors have been successfully used, for applications such as synthetic aperture radars, optical pattern recognition, optical image processing, fingerprint enhancement, and optical spectrum analyzers. The early work in optical signal processing and computing was basically analog in nature. In the past two decades, however, a great deal of effort has been expended in the development of digital optical processors.

Much work remains before digital optical computers will be widely available commercially, but the pace of research and development has increased through the 1990s. During the last decade, there has been continuing emphasis on the following aspects of optical computing:

- Optical tunnel devices are under continuous development varying from small caliber endoscopes to character recognition systems with multiple type capability.

- Development of optical processors for asynchronous transfer mode.

- Development architectures for optical neural networks.

- Development of high accuracy analog optical processors, capable of processing large amounts of data in parallel.

Since photons are uncharged and do not interact with one another as readily as electrons, light beams may pass through one another in full-duplex operation, for example without distorting the information carried. In the case of electronics, loops usually generate noise voltage spikes whenever the electromagnetic fields through the loop changes. Further, high frequency or fast switching pulses will cause interference in neighboring wires. On the other hand, signals in adjacent optical fibers or in optical integrated channels do not affect one another nor do they pick up noise due to loops. Finally, optical materials possess superior storage density and accessibility over magnetic materials.

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The field of optical computing is progressing rapidly and shows many dramatic opportunities for overcoming the limitations described earlier for current electronic computers. The process is already underway whereby optical devices have been incorporated into many computing systems. Laser diodes as sources of coherent light have dropped rapidly in price due to mass production. Also, optical CD-ROM discs are now very common in home and office computers.

Current trends in optical computing emphasize communications, for example the use of free-space optical interconnects as a potential solution to alleviate bottlenecks experienced in electronic architectures, including loss of communication efficiency in multiprocessors and difficulty of scaling down the IC technology to sub-micron levels. Light beams can travel very close to each other, and even intersect, without observable or measurable generation of unwanted signals. Therefore, dense arrays of interconnects can be built using optical systems. In addition, risk of noise is further reduced, as light is immune to electromagnetic interferences. Finally, as light travels fast and it has extremely large spatial bandwidth and physical channel density, Free-space optical techniques are also used in scalable crossbar systems, which allow arbitrary interconnections between a set of inputs and a set of outputs. Optical sorting and optical crossbar inter-connects are used in asynchronous transfer modes or packet routing and in shared memory multiprocessor systems.

it appears to be an excellent media for information transport and hence can be harnessed for data processing. This high bandwidth capability offers a great deal of architectural advantage and flexibility. Based on the technology now available, future systems could have 1024 smart pixels per chip with each channel clocked at 200MHz (a chip I/O of 200Gbits per second), giving aggregate data capacity in the parallel optical highway of more that 200Tbits per second; this could be further increased to 1000Tbits. Free-space optical techniques are also used in scalable crossbar systems, which allow arbitrary interconnections between a set of inputs and a set of outputs. Optical sorting and optical crossbar inter-connects are used in asynchronous transfer modes or packet routing and in shared memory multiprocessor systems.

In optical computing two types of memory are discussed. One consists of arrays of one-bit-store elements and the other is mass storage, which is implemented by optical disks or by holographic storage systems. This type of memory promises very high capacity and storage density. The primary benefits offered by holographic optical data storage over current storage technologies include significantly higher storage capacities and faster read-out rates. This research is expected to lead to compact, high-capacity, rapid- and random-access, radiation-resistant, low-power, and low-cost data storage devices necessary for future intelligent spacecraft, as well as to massive-capacity and fast-access terrestrial data archives. As multimedia applications and services become more and more prevalent, entertainment and data storage companies are looking at ways to increase the amount of stored data and reduce the time it takes to get that data out of storage. The SLMs and the linear array beam steerer are used in optical data storage applications. These devices are used to write data into the optical storage medium at high speed. The analog nature of these devices means that data can be stored at much higher density than data written by conventional devices. Researchers around the world are evaluating a number of inventive ways to store optical data while improving the performance and capacity of existing optical disk technology. While these approaches vary in materials and methods, they do share a common objective: expanded capacity through stacking layers of optical material. For audio recordings, a 150-MB minidisk with a 2.5-in. diameter has been developed that uses special compression to shrink a standard CD's 640-MB storage capacity onto the smaller polymer substrate. It is rewritable and uses magnetic field modulation on optical material. The minidisk uses one of two methods to write information onto an optical disk. With the minidisk, a magnetic field placed behind the optical disk is modulated while the intensity of the writing laser head is held constant. By switching the polarity of the magnetic field while the laser creates a state of flux in the optical material, digital data can be recorded on a single layer. As with all optical storage media, a read laser retrieves the data. Along with minidisk developments, standard magneto-optical CD technology has expanded the capacity of the 3.5-in. diameter disk from 640 MB to commercially available 1 GB storage media. These conventional storage media modulate the laser instead of the magnetic field during the writing process. Fourth-generation 8× 5.25 in. diameter disks that use the same technology have reached capacities of 4 GB per disk. These disks are used mainly in 'jukebox' devices. Not to be confused with the musical jukebox, these machines contain multiple disks for storage and backup of large amounts of data that need to be accessed quickly.

For audio recordings, a 150-MB minidisk with a 2.5-in. diameter has been developed that uses special compression to shrink a standard CD's 640-MB storage capacity onto the smaller polymer substrate. It is rewritable and uses magnetic field modulation on optical material.

Beyond these existing systems are several laboratory systems that use multiple layers of optical material on a single disk. The one with the largest capacity, magnetic super-resolution (MSR), uses two layers of optical material. The data is written onto the bottom layer through a writing laser and magnetic field modulation (MFM). When reading the disk in MSR mode, the data is copied from the lower layer to the upper layer with greater spacing between bits. In this way, data can be stored much closer together (at distances smaller than the read beam wavelength) on the bottom layer without losing data due to averaging across bits. This method is close to commercial production, offering

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capacities of up to 20 GB on a 5.25 in. disk without the need for altering conventional read-laser technology. Advanced storage magnetic optics (ASMO) builds on MSR, but with one exception. Standard optical disks, including those used in MSR, have grooves and lands just like a phonograph record. These grooves are used as guideposts for the writing and reading lasers. However, standard systems only record data in the grooves, not on the lands, wasting a certain amount of the optical material's capacity. ASMO records data on both lands and grooves and, by choosing groove depths approximately 1/6 the wavelength of the reading laser light, the system can eliminate the crosstrack crosstalk that would normally be the result of recording on both grooves and lands. Even conventional CD recordings pick up data from neighboring tracks, but this information is filtered out, reducing the signal-to-noise ratio. By closely controlling the groove depth, ASMO eliminates this problem while maximizing the signal-to-noise ratio. MSR and ASMO technologies are expected to produce removable optical disk drives with capacities between 6 and 20 GB on a 12-cm optical disk, which is the same size as a standard CD that holds 640 MB. Magnetic amplifying magneto-optical systems (MAMMOS) use a standard polymer disk with two or three magnetic layers. In general terms, MAMMOS is similar to MSR, except that when the data is copied from the bottom to the upper layer, it is expanded in size, amplifying the signal. According to Archie Smith of Storagetek's Advanced Technology Office (Louisville, CO), MAMMOS represents a two-fold increase in storage capacity over ASMO.

Technology developed by Call/Recall Inc. (San Diego, CA) could help bridge the gap between optical disk drives and holographic memories. Called 2-photon optical storage technology (which got its start with the assistance of the Air Force research laboratories and DARPA), the Call/Recall systems under development use a single beam to write the data in either optical disks with up to 120 layers, or into 100-layer cubes of active-molecule-doped MMA polymer. In operation, a mask representing data is illuminated by a mode-locked Nd:YAG laser emitting at 1064 nm with pulse durations of 35 ps. The focal point of the beam intersects a second beam formed by the second harmonic of the same beam at 532 nm. The second beam fixes the data spatially and temporally. A third beam from a HeNe laser emitting at 543 nm reads the data by causing the material to fluoresce. The fluorescence is read by a charge-coupled device (CCD) chip and converted through proprietary algorithms back into data. Newer versions of the system use a Ti:Sapphire laser with 200-fs pulses. Call/Recall's Fredrick McCormick said the newer and older approaches offer different strengths. The YAG system can deliver higher-power pulses capable of storing megabits of data with a single pulse, but at much lower repetition rates than the Ti:Sapphire laser with its lower-power pulses. Thus, it is a trade-off. Call/Recall has demonstrated the system using portable apparatus comprised of a simple stepper-motor-driven stage and 200-microwatt HeNe laser in conjunction with a low-cost video camera. The company estimates that an optimized system could produce static bit error rates (BER) of less than 9×10^{-13}. McCormick believes that a final prototype operating at standard CD rotation rates would offer BERs that match or slightly exceed conventional optical disk technology. Researchers such as Demetri Psaltis and associates at the California Institute of Technology are also using active-molecule-doped polymers to store optical data holographically. Their system uses a thin polymer layer of PMMA doped with phenanthrenequinone (PQ). When illuminated with two coherent beams, the subsequent interference pattern causes the PQ molecules to bond to the PMMA host matrix to a greater extent in brighter areas and to a lesser extent in areas where the intensity drops due to destructive interference. As a result, a pair of partially offsetting index gratings is formed in the PMMA matrix. After writing the hologram into the polymer material, the substrate is baked, which causes the remaining unbonded PQ molecules to diffuse throughout the polymer, removing the offsetting grating and leaving the hologram. A uniform illumination is the final step, bonding the diffuse PQ throughout the

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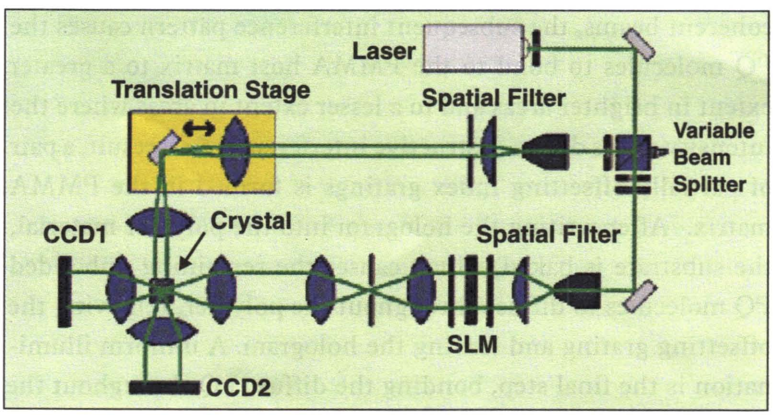
matrix and fixing the hologram in the polymer material. Storagetek's Archie Smith estimates that devices based on this method could hold between 100 and 200 GB of data on a 5.25-in diameter polymer disk.

More conventional approaches to holographic storage use iron-doped lithium niobate crystals to store pages of data. Unlike standard magneto-optical storage devices, however, the systems developed by Pericles Mitkas at Colorado State University use the associative search capabilities of holographic memories (*Figure* 3). Associative or content-based data access enables the search of the entire memory space in parallel for the presence of a keyword or search argument. Conventional systems use memory addresses to track data and retrieve the data at that location when requested. Several applications can benefit from this mode of operation including management of large multimedia databases, video indexing, image recognition, and data mining. Different types of data such as formatted and unformatted text, gray scale and binary images, video frames, alphanumeric data tables, and time signals can be interleaved in the same medium and we can search the memory with either data type. The system uses a data and a reference beam to create a hologram on one

Figure 3. Holographic me-mory cubes use a spatial light modulator to simultaneously search the entire memory for a searchable object – be it text, image, or something else. This associative memory search process promises significant benefits for database searching and other applications.



plane inside the lithium niobate. By changing the angle of the reference beam, more data can be written into the cube just like pages in a book. The current systems have stored up to 1000 pages per spatial location in either VGA or VGA resolutions. To search the data, a binary or analog pattern that represents the search argument is loaded into a spatial light modulator and modulates a laser beam. The light diffracted by the holographic cube on a CCD generates a signal that indicates the pages that match the sought data. Recent results have shown the system can find the correct data 75 percent of the time when using patterns as small as 1 to 5 percent of the total page. That level goes up to 95 to 100 percent by increasing the amount of data included in the search argument.

Suggested Reading

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