Optical Computing

2. Research Trends

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Researchers are using new conducting polymers to make transistor-like switches that are smaller and thousand times faster than the silicon transistors. Electricity-conducting organic molecules that are much thinner than semiconductor wires, are being teased into self-assembling. These advances promise super-tiny all-optical chips. In fact, progress in optical storage devices can now shrink an entire Library's book collection down to sugar-cube size. Optical computers could be leaving silicon number crunchers choking in the dust by decade's end.

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Introduction

In recent years, a number of devices that can ultimately lead us to real optical computers have already been manufactured. These include optical logic gates, optical switches, optical interconnections, and optical memory. High-density physical integration optical switching devices have been achieved. Optical devices can have switching speeds of the order of 10^{-15} seconds with power requirements as low as 10^{-6} watts. Two types of optical processors have been under active development, namely numeric and nonnumeric. Numeric processors include logic multiplication unit, optical arithmetic unit and optical correlator. Non-numeric processors for optical text processing and optical knowledge based processing have shown good results.

Keywords
Optical switching devices, organic polymer optical devices, optical computer trends.

Among the most crucial performance-limiting factors of today's very large-scale integrated circuits are the limited pin number and the low bandwidth of interconnections, rather than the chip's processing power. (For example, the Japanese Earth Simulator, a computer system developed by NEC, uses a processor IC with 5,000 pins.) Much more performance will be achieved if chip-to-chip data transfer can be realized by fast links leaving the circuit directly out from the chip's surface instead of via the chip's edge. Arrays of optical modulators or vertical surface emitting lasers, that can be flip-chip bonded onto complementary metal oxide semiconductor circuits, promise to offer a solution for the bottleneck in chip-to-chip communications.

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Optical interconnections for VLSI systems also offer massive parallelism and three-dimensional interconnection capabilities. During the last decade, significant advances have been achieved in the field of optoelectronics VLSI (OE-VLSI) and microelectronics. Arrays of OE-VLSI circuits linked together by 3-D optical interconnections based on free space optics offer a kind of natural pipeline. It is possible now to design circuitry within the OE-VLSI chip as an array processing structure. This will help to combine the two most popular parallel processing techniques: pipelining and array processing. This is of great interest for the design of innovative 3-D arithmetic units that can serve as the core for future 3-D processors. It is envisaged that such architectures offer potential for a significant increase of computing performance, which would not be possible by using only all-electronic technology. It may also be considered as a road map for a future massively parallel optoelectronic supercomputer system.

An interesting suggestion is that such systems can consist of multiple clusters, which can be directly mounted with a silicon spacer on a glass substrate. Inside the glass substrate, the optical interconnections are to run along zigzag paths. Additionally, diffractive optical elements are etched in a glass substrate's surface to realize the optical interconnections, which link the OE-VLSI circuit.

Optical computing technology is, in general, developing in two directions. One approach is to build computers that have the same architecture as present day computers but using optics. Another approach is to generate a completely new kind of computer, which can perform all functional operations in an optical mode. The research carried out to date suggests that all

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optical computers are far from reality and a hybrid system could be tested for typical mathematical/functional operations. Performance benchmark reports in this direction could push opto-electronic-computing systems out of laboratories and encourage more research towards cost effective user friendliness.

Another interesting area is holo-computing. Consider two apparently unrelated facts. First, the trend in all areas of high-end computing is towards greater parallelism. Second, because of its quantum nature, a photon has no path or position until it is detected. These facts get connected to the domain of holography. Holographic techniques will be central to photonic computing, provided substantial research continues towards material properties. Using the properties of holography and creating holograms with computers provide many computer-oriented applications. These include computer memories, pattern recognition, data encryption, optical contouring, CAD, medical imaging, etc. Optical memories are expected to be an integral part of high performance computing. Where research will take optical memories, it remains to be seen.

One of the emerging trends in the area of optical computing is the development of photonic devices. Optical interconnects promise to eliminate I/O bottlenecks in VHSIC chips, boards, and back-panes, increasing the processor power of high speed computing systems. The future lies in the development of massively parallel photonic switches relying on optically processed signal routing, monolithic integration of optoelectronic elements, and an architecture optimized to exploit the speed and parallelism of optical interconnections. Such developments will pave way for high speed routing in broadband networks as well as optically interconnected multiprocessors in future.

We are in an era of daily explosions in the development of optics and optical components for computing and other applications. Photonics is booming in industry and universities worldwide. Data traffic is growing worldwide at a rate of 100% per year, while in the US; data traffic is expected to increase 300%

annually. The requirement for high data rate transfer equipment is also expected to continue increasing. Electronic switching limits network speeds to about 50 Gigabits per second. Terabit speeds are needed to accommodate the growth rate of the Internet and the increasing demand for bandwidth-intensive data streams.

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Some Current Research

High performance computing (HPC) has gained momentum in recent years, with efforts to optimize all the resources of electronic computing and researcher brainpower in order to increase computing throughput. Optical computing is a topic of current support in many places, with private companies as well as governments in several countries encouraging such research work. For example, much of the optical computing research in Japan is performed under the auspices of the Real World Computing – Real World Intelligence/Parallel and Distributed Computing project. That research focuses on next generation computing systems and development of support technologies.

Most components that are currently very much in demand are electro-optical (EO). Such hybrid components are limited by the speed of their electronic parts. All-optical components will have the advantage of speed over EO components. Unfortunately, there is an absence of known efficient nonlinear optical (NLO) materials that can respond at low power levels. Most all-optical components require a high level of laser power to function as required.

A group of researchers from the University of Southern California, jointly with a team from the University of California, Los Angeles, have developed an organic polymer with switching frequency of 60 GHz. This is three times faster than the current industry standard, lithium niobate crystal-based devices. The California teams have been working to incorporate their material into a working prototype. Development of such a device could revolutionize the information superhighway and speed data processing for optical computing.

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Another group at Brown University and the IBM Almaden Research Center (San Jose, CA) has used ultrafast laser pulses to build ultrafast data-storage devices. This group was able to achieve ultrafast switching down to 100ps. Their results are almost ten times faster than currently available 'speed limits'. Optoelectronic technologies for optical computers and communication hold promise for transmitting data as short as the space between computer chips.

In Japan, NEC has developed a method for interconnecting circuit boards optically using Vertical Cavity Surface Emitting Laser arrays (VCSEL). Researchers at Osaka City University reported a method for automatic alignment of a set of optical beams in space with a set of optical fibers.

Other researchers at NTT have designed an optical backplane with free-space optical interconnects using tunable beam deflectors and a mirror. The project achieved 1000 interconnections per printed-circuit board; with throughput ranging from 1 to 10 Tb/s. Optics has a higher bandwidth capacity than electronics, which enables more information to be carried and data to be processed. This arises because electronic communication along wires requires charging of a capacitor that depends on length. In contrast, optical signals in optical fibers, optical integrated circuits, and free space do not have to charge a capacitor and are therefore faster.

The Role of NLO in Optical Computing: the Need for New Materials

The field of optical computing is considered to be the most multidisciplinary field and requires for its success collaborative efforts of many disciplines, ranging from device and optical engineers to computer architects, chemists, material scientists, and optical physicists. On the materials side, the role of nonlinear materials in optical computing has become extremely significant. Nonlinear materials are those, which interact with light and modulate its properties.

For example, such materials can change the color of light from being unseen in the infrared region of the color spectrum to a green color where it is easily seen in the visible region of the spectrum. Several of the optical computer components require efficient nonlinear materials for their operation. What in fact restrains the widespread use of all optical devices is the inefficiency of currently available nonlinear optical materials, which require large amounts of energy for responding or switching. In spite of new developments in materials, presented in the literature daily, a great deal of research by chemists and material scientists is still required to enable better and more efficient optical materials. Organic materials have many features that make them desirable for use in optical devices, such as high nonlinearities, flexibility of molecular design, and damage resistance to optical radiation; however, processing difficulties for crystals and thin films has hindered their use in devices. Still, some organic materials belonging to the classes of phthalocyanines and polydiacetylenes are promising for optical thin films and waveguides. Phthalocyanines are large ring-structured porphyrins for which large and ultrafast nonlinearities have been observed. These compounds exhibit strong electronic transitions in the visible region and have high chemical and thermal stability up to 400°C. The third order susceptibility of phthalocyanine, which is a measure of its nonlinear efficiency, has been found to be more than a million times larger than that of the standard material, carbon disulfide. This class of materials has good potential for commercial device applications, and has been used as a photosensitive organic material, and for photovoltaic, photoconductive and photo-electrochemical applications.

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Polydiacetylenes are zigzag polymers having conjugated (alternating) mobile π-electrons for which the largest reported nonresonant (purely electronic) susceptibility for switching has been reported. Consequently, polydiacetylenes are among the most widely investigated class of polymers for nonlinear optical applications. Their subpicosecond time response to laser signals makes them candidates for high-speed optoelectronics and in-

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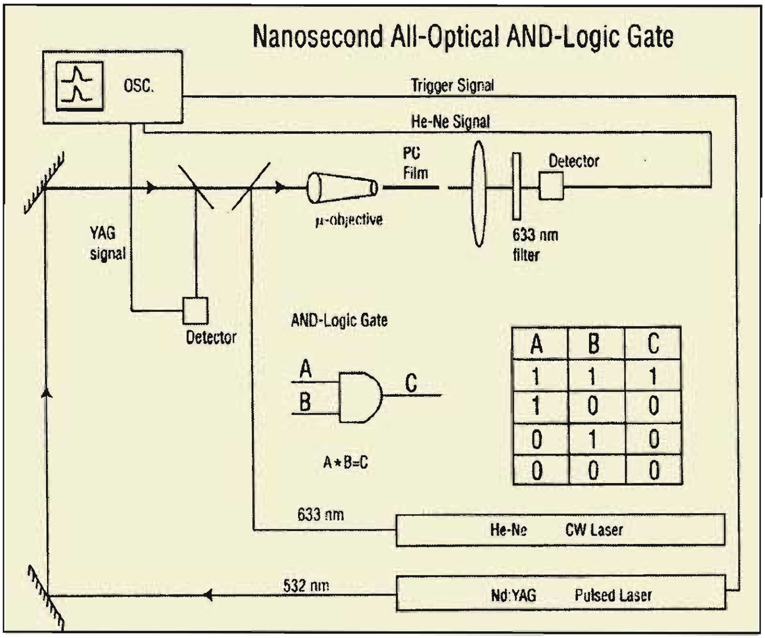
formation processing. Some of these materials can be intrinsically bi-stable when deposited in thin-film layers. Optical bistable devices and logic gates are the equivalent of electronic transistors. They switch light ON and OFF. They are also useful as optical cells for information storage.

Advances in Photonic Switches

Logic gates are the building blocks of any digital system. An optical logic gate is a switch that controls one light beam by another; it is 'ON' when the device transmits light and it is 'OFF' when it blocks the light. Abdeldayem and others [1] of the NASA Marshall Space Flight Center demonstrated two fast all-optical switches using phthalocyanine thin films and polydiacetylene fiber in their laboratory. The phthalocyanine switch is in the nanosecond regime and functions as an all-optical AND logic gate, while the polydiacetylene one is in the picosecond regime and exhibits a partial all-optical NAND logic gate.

To demonstrate the AND gate in the phthalocyanine film, Abdeldayem and others [1] waveguided two focused collinear laser beams through a thin film (~1 mm) of metal-free phthalocyanine film. They used the nanosecond green pulsed Nd:YAG laser with a red continuous wave (cw) He-Ne beam. At the output a narrow band filter was set to block the green beam and allow only the He-Ne beam. When the transmitted beam was detected on an oscilloscope from fast photo-detector, it was found that the transmitted He-Ne cw beam was pulsating with a nanosecond duration and in synchronous with the input Nd:YAG nanosecond pulse. This demonstrated the characteristic table of an AND logic gate. A schematic of the overall experiment is shown in *Figure* 1.

A picosecond switch was demonstrated by the same group [1] with a setup quite similar to the one shown in *Figure* 1, except that the phthalocyanine film was replaced by a hollow fiber (refractive index of 1.7) filled with a polydiacetylene (refractive



A	B	C
1	1	1
1	0	0
0	1	0
0	0	0

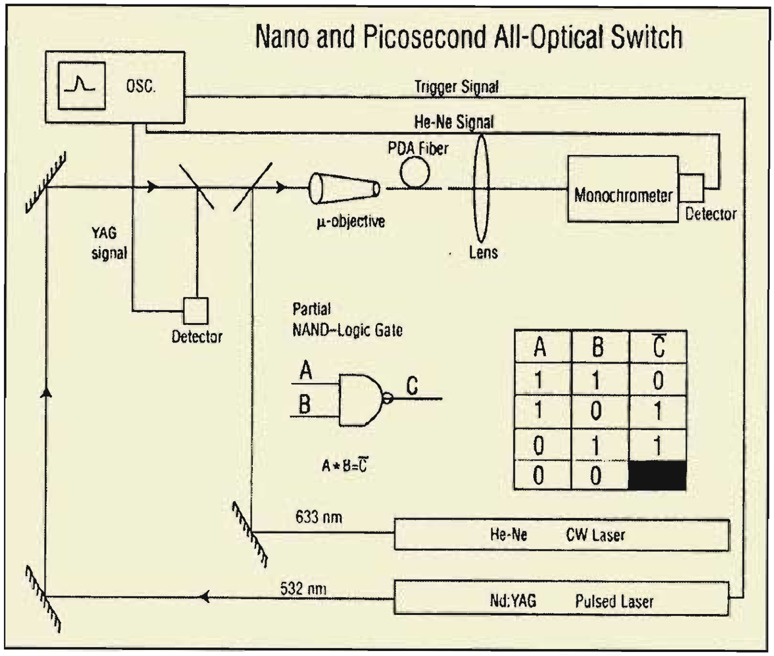
Figure 1. A schematic of the nanosecond all-optical AND logic gate setup.

index of 1.2). A mode locked Nd:YAG green picosecond laser pulse was sent collinearly with a red cw He-Ne laser (632.8 nm) onto one end of the fiber. At the other end of the fiber a lens was focusing the output onto the narrow slit of a monochrometer with its grating set for the red He-Ne laser. It was found that with the He-Ne beam OFF, the Nd:YAG pulse induced a week fluorescent picosecond signal (40 ps) at 632.8nm that was observed as a picosecond pulse on the oscilloscope. The signal disappeared each time the He-Ne beam was turned on. These results exhibited a picosecond respond in the system and demonstrated three of the four characteristics of a NAND logic gate as shown in *Figure* 2.

Research in India

In India, technological changes have been taking place very fast. The primary objective has been to support national socio-economic growth and hence funds were provided accordingly. The areas of space exploration, earth resource utilization, communications, transport, image processing, biotechnology, etc. have led to extensive computer technologies including hardware,

Figure 2. A schematic of the picosecond all-optical NAND logic gate set-up.



system and applications software developments, as well as reinforcing user confidence to utilize such resources. Much of this research, and especially in applications, is highly multidisciplinary and it was soon realized that HPC capability is a prerequisite and, thus initiatives to explore other aspects began. Topics such as quantum computing, optical computing and neural/ DNA computing are being considered. There was even one effort on combining two or more new computing forms along with the conventional ones. Nevertheless, Indian progress in optical computing has been only at a few selected premier research institutes and is yet to make its mark.

India's Department of Science and Technology (DST) has taken several innovative initiatives to support new technologies. Aimed at the year 2020 AD (and the vision for the new millennium), the Technology Information, Forecasting and Assessment Council (TIFAC) has started the Center of Relevance & Excellence (CORE), which is, at the moment, concentrating on VLSI, information security and networking. TIFAC is an autonomous organization of the Government of India's DST. Further, last year, the Council of Scientific and Industrial Research (CSIR) began its New Millennium Indian Technology Leadership Initiative (NMITLI) in an effort to attain global leadership in a few selected niche areas.

The Ministry of Information Technology (MIT) has also initiated a Photonics Development Program which has a long term objective of developing core technologies and applications related to next generation electronics, computers and communications systems. Under this program, some funded projects are continuing in fiber optic high speed network systems, opto-electronics technology, photonic switching multiplexing and networking, and microwave photonics. There is also a proposal for the Ministry to establish a Center for Photonics. The researchers in India realize the importance of optical computing and are in tune with government support to initiate a few critical activities in this direction. Some of them plan to join hands for collaborative efforts. The institutes/organizations that are involved include IITs at Mumbai, Delhi, and Chennai; Indian Institute of Science (IISc), Bangalore; Tata Institute of Fundamental Research (TIFR), Mumbai; Center for Advanced Technology (CAT), Indore; Bhabha Atomic Research Center (BARC), Mumbai; Defense Research and Development Organization (DRDO), New Delhi; CSIR Laboratories, and Center for Artificial Intelligence Research (CAIR), Bangalore. Some other universities will also join this initiative. Typical research issues to be addressed include developing new laser diodes, photon detectors, tunable wavelength sources, and nonlinear material studies for faster switches. Research efforts on novel nanoparticle thin film or layer studies for display devices are also in progress.

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The sending of many different wavelengths down the same optical fiber is known as Wavelength Division Multiplexing (WDM). Using this technology, modern networks in which individual lasers can transmit at 10 Gigabits per second can have several different lasers each giving out 10 Gbit/s through the

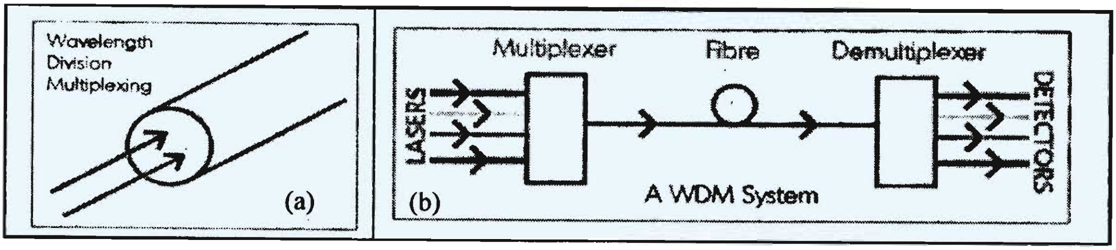

Figure 3. (a) Schematic diagram of wavelength division multiplexing, showing two wavelengths being multiplexed into the optical fiber.
(b) A typical WDM system with a demultiplexer before the detectors to read information sent through the fiber.

same fiber at the same time. Systems being deployed at present will usually have no more than maybe 32 wavelengths, but technology advancements will continue to make a higher number of wavelengths possible. The act of combining several different wavelengths on the same fiber is known as multiplexing. At the receiving end, these wavelengths need to be separated again, which is known, logically enough, as demultiplexing. Each wavelength will then need its own light detector to convert it back into useful information (*Figure* 3). At the Indian Institute of Technology (IIT), Mumbai, efforts are in progress to generate a white-light source from a diode-laser based fiber amplifier system in order to provide wide bandwidth WDM communication channels. The Ministry of Information Technology is funding this research.

The Ministry of Information Technology has also provided funding to TIFR for conducting Quantum Computing utilizing optical approaches [2]. In this research initiative, rapid programmable ultrafast optical pulse shaping is being demonstrated at 1550 nm wavelength, the important wavelength range for applications to optical communications using commercial ultrashort laser pulses in picosecond (10^{-12} s) and femtosecond (10^{-15} s) range. In particular to the optical information channel, what has been achieved with ultrafast optical pulse shaping can be viewed as an optical spectral encoder with rapid update rate. One of the important and promising applications of this spectral encoder is for high-speed optical communication. Shaping ultrafast pulses is nontrivial since there are no electronic devices that can work on these timescales. If the optical pulse that one wishes to shape has a temporal duration of fs or ps, then a modulator that works on this timescale is required.

The idea of shaping a pulse by sending it through a modulator, such as a Mach-Zehnder, is referred to as direct pulse shaping. Current modulators can operate at 60GHz, which is much slower than necessary to shape a femtosecond pulse. Therefore, the technique of indirect pulse shaping, which includes Liquid Crystal Modulators (LCM pulse shaping), Acousto-Optic Modulator (AOM pulse shaping), and time-stretched pulse shaping, is used. The choice of which pulse-shaping apparatus to use may depend on the particular application; each technique has different advantages [3].

In the particular technique followed at TIFR, a grating spreads the pulse, so that each different spectral component maps onto a different spatial position. The collimating lenses and grating pair are set up in a $4F$ configuration (F being the focal length of the collimating lenses), and in the center of the $4F$ system, an element is placed that will modulate the spectrum (see *Figure* 4). The essential concepts of Fourier transformation of the incident beam are utilized. In the case that AOM is the encoding element, there is a huge difference between sound and light speeds in the

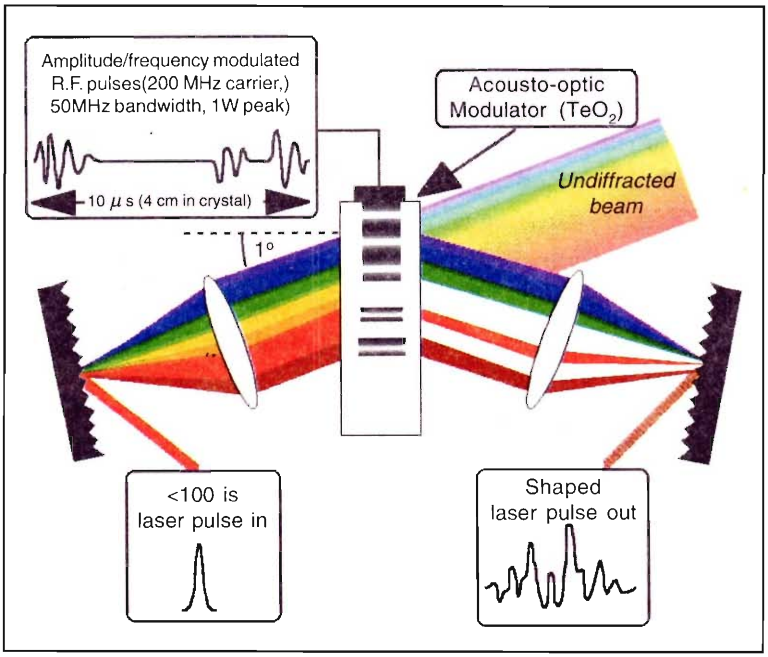

Figure 4. A schematic of the acousto-optic modulated pulse shaping technique.

Typical DWDM is a fiber-optic transmission technique that employs light wavelengths to transmit data parallel-by-bit or serial-by-character.

AOM crystal. Since the ratio between these two is about 1 to 1 million, one can use a MHz electrical signal to achieve THz programmable modulation of an optical signal and still keep a reasonable update speed. In practice, high resolution spectral encoding is, by definition, a variation of Dense Wavelength Division Multiplexing (DWDM) and can be used to significantly improve the bandwidth efficiency.

Typical DWDM is a fiber-optic transmission technique that employs light wavelengths to transmit data parallel-by-bit or serial-by-character. This technology puts data from different sources together on an optical fiber, with each signal carried at the same time on its own separate light wavelength. Each channel carries a time division multiplexed (TDM) signal. In a system with each channel carrying 2.5 Gbps (billion bits per second), up to 200 billion bits can be delivered a second by the optical fiber. Since each channel is demultiplexed at the end of the transmission back into the original source, different data formats being transmitted at different data rates can be transmitted together. The idea behind the variation being attempted at TIFR can be illustrated in the following way: Start with a 100 fs Full-Width at Half Maximum (FWHM) optical pulse and encode, for example, 16 amplitude on-off-keying return-to-zero (RZ) format bits in its spectrum; in the worst possible case this would broaden the pulse by a factor of 16–to about 1.6 ps FWHM. The encoded pulses can, therefore, be well confined in a 4 ps optical switching window without much distortion to the encoded spectrum. By doing this, the Time Division Multiplexing (TDM) system can benefit from spectrum encoding by a factor of 16 and the achievable Data Translation Rate (DTR) can be as high as 4 Tbps.

The Indian Institute of Technology (IIT), Delhi continues to do some basic work in the area of software development for assembling optical computers using genetic algorithms. The optimization is done for the optical array assignment problems that arise in the assembly of optical computers using imperfect optical arrays. The important feature of the algorithms being considered is that they increase the utilization of the arrays through transformations such as translation, rotation, and a combination of both. IIT, Delhi has taken a leading role in algorithmic work in optical computing, their faculty has made fundamental contributions in the areas of optical neural networks, optical encryption, non-linear optical characterization, optical storage, pattern recognition, and optical image processing.

Conclusion

Research in optical computing has opened up new possibilities in several fields related to high-performance computing, high-speed communications, and parallel algorithm design. To design algorithms that execute applications faster, the specific properties of optics must be considered, such as their ability to exploit massive parallelism, and global interconnections. As optoelectronic and smart pixel devices mature, software development will have a major impact in the future and the ground rules for the computing may have to be rewritten.

Suggested Reading

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