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Soviet General Purpose Optical Computing Technology: Progress and Prospects

A Technical Intelligence Report

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Soviet General Purpose Optical Computing Technology: Progress and Prospects

A Technical Intelligence Report

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Soviet General Purpose Optical Computing Technology: Progress and Prospects

Preface

Information available as of 1 August 1989 was used in this report.

This paper explores, in depth, the level of Soviet development in the key component and architectural technologies required for fabricating an all-optical general purpose computer. Such a computer would offer Soviet military planners a means to overcome some limitations of their lagging electronic-computing industry and could rival the performance of Western supercomputers. In many cases, current Soviet computing limitations constrain the performance of Soviet weapon systems; lessening or removing them would open up the possibility of vastly improved weapon performance. As each individual technology matures and is developed as part of a general purpose optical computer, it could potentially be integrated into military optical data-processing systems.

For the past 30 years, the USSR has been investigating optical-computing techniques with potential applications as diverse as synthetic-aperture radar (SAR) processing, antiballistic missile (ABM) defense radar processing, signal processing, medical imaging, and supercomputing. The USSR, with a permanent commission on optical data processing in the Academy of Sciences, has maintained the largest optical-processing research effort in the world. The Soviets' accomplishments dwarf those of the West in many component technologies. Optical computers would offer advantages of very high data rates, inherent parallel processing, and greater flexibility than electronic processors.

Because of increased Soviet interest in the application of optical technologies to military systems, several key areas of Soviet research in optical techniques have been the subject of earlier intelligence reports. [ ]

Soviet General Purpose Optical Computing Technology: Progress and Prospects

Summary

The Soviets have strengthened their lead over the West in the development and use of optical concepts and components intended ultimately for high-speed general purpose computers. This lead is most evident in Soviet progress in developing spatial light modulators (SLMs)—a maturing technology ready for dissemination from the laboratory to Soviet industry as well as marketing on an international scale. SLMs provide the optical basis for performing logic operations and are the key elements in the development of wide-band optical processors for radar, sonar, nonacoustic antisubmarine warfare (ASW) reconnaissance, and image processors. We believe that the Soviets, aided by their current five- to 10-year lead over the West, will maintain their dominance in the SLM field for the next decade because of their large-scale commitment, trained manpower, and in-place manufacturing capability.

In general, we find that Soviet optical-computing research has involved fundamental algorithms unique to the optical regime, rather than analogs of electronic techniques done optically. Much of this uniqueness results from the natural parallelism of optical computing and is particularly well suited to optical signal processing. We believe the development of optical processing could help alleviate existing Soviet deficiencies in electronic signal processing. Optical processing offers the ability to implement pattern logic, use holographic storage, and possibly process discrete and analog signals with the same processing elements. Aided by excellence in the areas of optical memories, mathematics, crystal growth, and new novel number representations, the Soviets have developed, and we feel will continue to develop, an advanced optical program without requiring Western technology.

Substantial Soviet research is under way on optics-based processing. The Soviet optical development program, in fact, seems to be many times larger than the US program. Although Soviet (and also Western) scientists recognize the theoretical capabilities and advantages that optical computing affords, they have yet to achieve practical implementation of the technology. Major problem areas include the lack of high-speed optical devices, interface problems between optical and electronic components, and the need for advanced algorithms that will realize the inherent parallelism of optical processing (see table 1). Although the Soviets have devoted enormous research efforts to each of these areas, we believe their technological advances to date are insufficient to support a general purpose

Table 1
Key Technical Areas of Optical Computing

Technical Area	Problem Areas	Level of Soviet Effort	Progress
Spatial light modulators	High-speed, low-power devices have not been developed	High	Many reproducible SLM types, at least one offered commercially on the international market
Optical memories	Parallel readout necessary for optical computing applications	High	Well-developed holographic storage technology
Arithmetics	Parallel algorithms must be developed	Medium	Extensive research in residue arithmetic theory
Optical architectures	Non von Neumann reconfigurable processors must be developed	High	Well-developed theory of control operator method, tabular processing
Optical interconnections	Programmable interconnects required	Low	R&D only
Integrated optics	Process controls and materials technology are not mature	Medium	R&D only

optical computer. We believe that optics will permeate Soviet general purpose digital processors in an evolutionary rather than revolutionary manner, when their use provides distinct technological advantages (for example, interconnects, clock distribution, and higher data-flow rates). The gradual increase in Soviet optoelectronic hybridization of future computers will at some stage result in what can most aptly be described as an optical computer, but not before the year 2000.

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Soviet General Purpose Optical Computing Technology: Progress and Prospects

Introduction: Why Optics?

Because modern computational problems increasingly demand greater computing power, new computers must operate faster and faster to provide solutions in an acceptable time frame. As computing speeds increase, conventional electronic-computer technology approaches fundamental physical limits on computation speed. Faster computations generally require smaller, more densely packaged electronic components with physically shorter interconnecting signal paths in order to move data signals quickly between them. Smaller sizes result in greater power dissipation per unit volume (increased cooling requirements). Because interconnecting wire becomes so small, the number of electrons may be insufficient to reliably carry the signal at the required data rates. Other undesirable effects result from the interaction of electrons in adjacent closely spaced conductors. Recent demands for increases in speed have prompted computer designers to turn to parallel computing architectures as the primary route to faster computing, allowing several processors to simultaneously solve separable parts of a computing problem.

Optical systems have the potential for significant advances in most of the previously cited problem areas that limit electronic computers. (See appendix A for a discussion of optical devices using photons to perform the conventional role of electrons in switching devices.) In addition to an inherent parallel architecture, optical signals—using photons rather than electrons—can propagate through each other with essentially no interaction and can travel in parallel without interference or crosstalk. Interconnections between components can be implemented with optical wave guides or simply by using free-space propagation. Optical components also may be more flexible to use and simpler to implement than their electronic counterparts. For example, a single optical element may be able to assume any of several logic functions, and switch among these states between machine cycles. Rather than serving only as a direct analog to a electronic digital computer, an optical computer would allow implementation of fundamentally different, and potentially better, algorithms and processing methods. Algorithms suitable for and exploitative of optical computing probably will be very different from those used with conventional electronic computers.

Although some researchers envisage optical computers a thousand times faster than today's supercomputers, most are cautious and believe that optical computing will be more evolutionary than revolutionary. At present, few Western or Soviet researchers are advocating the design of a general purpose computer based exclusively on optical technology. Rather, most researchers believe that the particular advantages of optics over electronics can best be realized either in specialized computational devices such as signal processors, or as component parts of a hybrid optoelectronic machine, culminating over time as a largely optical computer. In October 1985, N. G. Basov, director of the Lebedev Physics Institute (FIAN), USSR Academy of Sciences, Moscow, endorsed this concept by stating that there is no real interest or program in the USSR for optical computers, but added that Soviet researchers had identified promising mathematical methods for use in optical computing.

The Soviet Optical-Processing Effort

In terms of researchers, funding, and number of identified facilities, the USSR clearly has the largest optical data-processing (ODP) effort in the world today. The Soviets have a permanent commission on ODP in the Academy of Sciences to organize efforts in this area, identify problems of implementation, and coordinate the development activity. Soviet ODP research efforts are systematically apportioned among

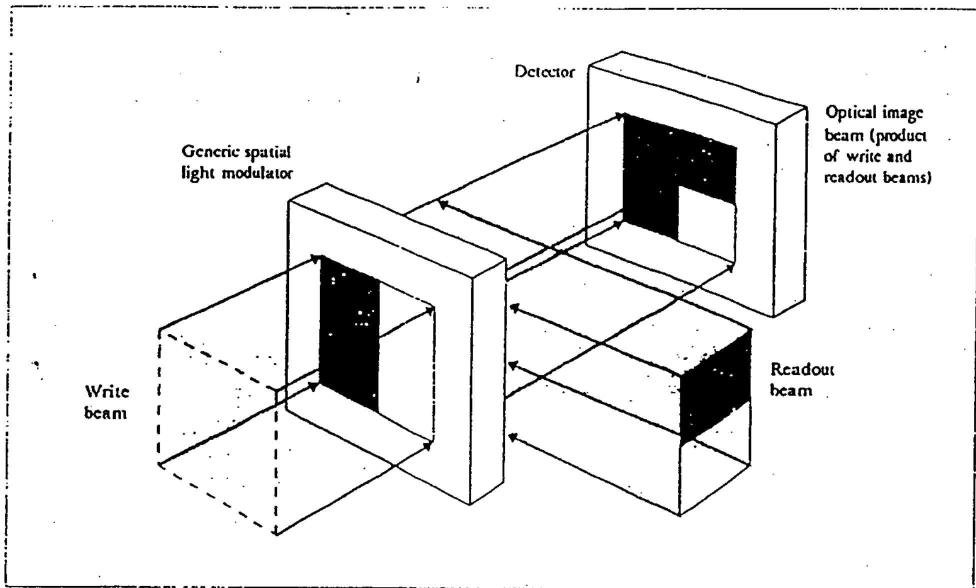
Table 2
A Brief History of Soviet Development of Optical Information Processing

Early 1960s	Soviets succeed in designing antennas using optical-modeling methods.
1966	Commissions explore applications of optical processing and holography to various military requirements.
1968	Ministry of Defense Industry reorganizes to foster optical technology transfer to weapon systems.
1970	Scientific Council established for the problem of "holography" to organize materials and device R&D at some 60 institutes from the Academy of Sciences and several ministries.
1974	A Soviet commission forecasts ODP-based weapon systems implementation by 1995. Control operator method (COM) developed at FIAN to design flexibility into massively parallel optical processors.
1975	Soviet goal set for the development of an optical digital computer by 1990 to operate at 10[illegible] operations/second.
1976	Some 10 to 12 different optical computers developed by FIAN at Novosibirsk.
1978	Optical correlator of GRU (military intelligence organization) locates airplanes, and invention of advanced SLMs gives USSR the lead in critical device technology. Random access memory (RAM) holographic memory developed and enters production. Soviet radar uses acousto-optic multichannel spectrum analyzer. Soviets announce development of the PRIZ (transliteration of Russian phrase for image transformer), a new generation of SLMs.
1979	Kartsev-Marshalko optoelectronic computer architecture developed using the control operator design philosophy and organized to overcome the speed disparity between optical processors and available electronic devices with which the processors must interface.
1980	Soviets boast USSR will leapfrog electronic data processing (EDP) with ODP.
1987	Soviets announce development of the PRIM (hybrid acronym derived from PROM and PRIZ) incorporating the best features of both the PROM (Pockels Readout Optical Modulator) and PRIZ SLMs. FIAN develops efficient lasing CRT (cathode ray tube.)
1988	Soviets announce the EPOS SLM for processing periodic signals. (EPOS is a Russian acronym for "electro-optic converter of optical signals."
1989	Soviet liquid-crystal light valve (LCLV) organic polymeric photoconductor available for commercial sale.

various Academy of Sciences and other institutions. We see this apportionment as a sign of a well-formulated approach to developing this technology. Aided by excellence in the fields of optical memories, mathematics, crystal growth, and new novel number representations, the Soviets have developed, and we feel will continue to develop, an advanced optical program without Western technological input

In 1984 a panel of US academic and industrial experts reviewed Soviet open literature in optical computing and concluded that the USSR had a three- to seven-year lead over the United States in key aspects of ODP technology. This lead was assessed to be the result of a 1970 decision to pursue ODP technology actively while the United States pursued advancements in microelectronic technology. (See table 2 for the history of the development of Soviet ODP.) Advantages the United States initially may have had in optical technologies were fragile and easily surpassed. Since the 1984 review, we find that an expanded Soviet commitment, trained manpower, and in-place manufacturing capability has lengthened that lead

Figure 1
Spatial Light Modulator



A spatial light modulator generally modulates the amplitude or phase of a "readout" light beam as a function of the intensity of a controlling "write" light beam. Many SLMs have a reflective structure in which the controlling write beam is incident on one side and the readout beam is reflected from the other side, with an effective reflectivity proportional to the write-beam intensity. The reflected beam forms a third, output image beam—a product of the two-dimensional information patterns on the write beam and readout beam. Finally, if data are encoded onto the readout beam as well as the write beam, the SLM can perform mathematical multiplications on patterns such as two-dimensional matrices.

Soviet SLMs

Technical Summary

For general purpose computing, large arrays of optical switches will be used to hold information in a data plane called a spatial light modulator (SLM), performing the same function as electronic transistors (see figure 1). On the basis of open scientific publications and [ ], we believe that the USSR leads the West by a substantial margin—perhaps as much as a decade both in the theory and fabrication of SLMs

Early SLMs were of the Pockels Readout Optical Modulator (PROM) type—not to be confused with the electronic "Programmable Read Only Memory" component, which is known by the same acronym. PROM was introduced in the United States in 1972, but was poorly understood until the Soviets developed the first correct physical/mathematical model several years later. The Soviets generally are regarded by Western researchers as having surpassed the West in SLM technology with their introduction of the PRIZ device in 1978. ("PRIZ" comes from the transliteration of the Russian phrase for image transformer.) The PRIZ, discussed in more detail later, reportedly has significant technical advantages as a signal-processing device for radar applications.

Very recent Soviet work on new types of SLMs—the PRIM (a hybrid acronym derived from PRIZ and PROM) and the EPOS (Russian-language acronym for electro-optic converter of optical signals), introduced in 1987-88—also are significantly ahead of Western SLMs. Because of their unique optical characteristics—such as inherent edge detection for moving-target indicators—we believe the new Soviet devices will have military applications in radar-warning equipment and other electronic-warfare applications.

In the field of liquid-crystal SLMs, the Soviets build devices that are consistently faster than any available in the West. According to [redacted] the Soviets soon will begin to market these devices internationally.

Open-source literature and [redacted] indicate the key Soviet institutes doing extensive work with SLMs are:

- The Ioffe Physico-Technical Institute (FTI), Leningrad.
- The Lebedev Physics Institute (FIAN), Moscow.
- The Institute of Automation and Electrometry (IAE), Novosibirsk.

Additional key institutes are given in table 3.

The Soviets apparently have a well-established mechanism for fabricating adequate quantities of various SLMs and disseminating them to researchers and application engineers. On numerous occasions Ioffe PRIZ and Lebedev liquid-crystal devices have been seen in Soviet institutes. Reporting [redacted] indicates that the Soviets are methodically exploring each possible application for their new indigenous devices and are enjoying great success with their new developments in SLMs. The development of the EPOS specifically for work with periodic signals is indicative of the intensive Soviet research geared to produce devices for limited applications based on proven technology. Overall, we believe the Soviet work on SLMs shows signs of a maturing technology ready for dissemination from the laboratory to industry.

PROM and PRIZ SLMs

The PROM SLM uses a crystal of bismuth-silicon oxide or bismuth-germanium oxide cut on the [111] plane and works on the basis of the linear electro-optic (or Pockels) effect. An electric field applied to a crystal causes variations in the crystalline structure, which linearly modifies the crystal's index of refraction. This electrically induced local change in the index of refraction is used to modulate the light incident on the PROM to perform computational operations. In digital computer terms, the PROM is a discrete light gate in the form of a matrix, each of whose elements executes logic operations on 1 data bit.

Building on their theoretical work, the Soviets now are judged by US researchers to have surpassed the West in both quality and variety of their SLMs, with their improvements to device architectures and with their generally superior PRIZ device introduced in 1978. The PRIZ was developed by Dr. Anatoly V. Khomenko and Dr. M. P. Petrov at LFTI. The device is made from the same material as the PROM and also works on the basis of the Pockels effect. But the PRIZ is cut along the [110] axis, so that the applied electric field that modifies the index of refraction is perpendicular to the incident light. This transverse electric field gives the PRIZ unique modulation characteristics

Although the PRIZ lacks some of the spatial resolution of the PROM device, it is reported to be two orders of magnitude superior to the PROM in sensitivity. The PRIZ actually responds to the spatial

Table 3
Key Soviet Institutes Involved in Optical Computing Research

Institute Name	Acronym	Type of Research Performed
Lebedev Physics Institute	FIAN	Involved in work related to lasers, materials, SLMs, laser diodes, optical memory systems, and a significant amount of pattern recognition work.
Institute of General Physics	IOFAN	Has traditionally worked on high-power lasers, military applications, phase-conjugate optics, but not ODP. Recently, researchers at IOFAN have begun presenting papers at optical computing conferences on picosecond (psec) laser pulses, integrated optics, psec optical gates, and switching networks (for example, optical computing elements).
Ioffe Physico Technical Institute (Leningrad)	FTI	Works in fiber optics, integrated optics, holographic research, ODP, SLM development, CCDs, scanistor development, and optical materials.
Shuvalov Quantum Radioelectronics Laboratory	LFTI	Developer of the PRIZ, volume holographic work, and acousto-optical materials.
Institute of Radio Engineering (Moscow)	IRE	Wide-band signal processing, AO processing, optical logic with gratings, optical correlators, integrated optics, and semiconductor holographic film that develops in several nanoseconds.
Institute of Automation and Electrometry (Novosibirsk)	IAE	Transitions of technology to industry, performs applications work, and fabricates hardware concerning optical memories and optical processors.
Moscow Physico Technical Institute	MFTI	Works on memories, optical logic, and holographic logic.
Polyus Scientific Research Institute, Ministry of Electronics Industries (Moscow)		Has developed various solid-state lasers for ODP and optical computing devices.
Moscow Acoustic Institute		Works on detailed system fabrication of acousto-optic devices.
Vavilov State Optics Institute (Leningrad)	GOI	Has fabricated weather radar optical processors and systems like the Gatchina holographic document-storage system.
Scientific Research Institute of Radio Physics (Gor'kiy)	NIRFI	Works with materials for optical memories.
Moscow Engineering Institute	MEI	Has worked with various radars and optical signals.
Kalinin Leningrad Polytechnic Institute		Has a key Soviet antiballistic missile researcher who has published several ODP papers.
Moscow State University	MGU	Multisensor image processing and some optical processing and SLM work.
Leningrad Institute of Aviation Instrument Company	LIAP	Works on optical signal processing, acousto-optics, and radar development.
All-Union Scientific Research Institute of Optics and Physical Measurements	VNIIOFI	Optical processing work, holography, and radar applications.
Kazan' Aviation Institute	KAI	Engaged in holography for radar applications.
Kiev Physics Institute		Nonlinear optics, optical computing, signal processing, and phase conjugation.
Leningrad Institute of Precision Mechanics and Optics	LITMO	Works on optical processing.
Moscow Research Institute of Instrument Building	MNIIPS	Works on antenna patterns, holography, and holographic computers.
Lumumba	MUDN	Works on optical waveguides and integrated optics.
All-Union Scientific Research Institute for Radio-Physical Measurements	VNIIRI	Works on holography for radar applications.
Institute for Problems of Information Transmission	IPPI	Works on holography for radar applications.

derivative of an image (giving it an enhanced edge-detection capability) and can be used so that it is sensitive only to input data that changes. We believe this characteristic makes the PRIZ a natural moving-target indicator when used for radar signal processing. The ability to detect only moving targets gives the PRIZ great potential to reject clutter when looking for targets with low radar cross section. The Soviets have explicitly stated that the PRIZ and PROM are being developed for military applications.

Soviet PROMs and PRIZs have been tested in US laboratories. The PRIZ devices were found to perform as well as the Soviets claimed, and the PROMs—originally reverse-engineered from US PROMs—were found to be superior to US devices. A leading US laboratory attempted to construct a PRIZ device using openly published Soviet information about its fabrication and principles of operation, but the experiment was not successful. (It is not known if this failure was due to undocumented process control steps or intentional omissions by the Soviets.

Liquid-Crystal SLMs

Liquid-crystal SLMs—also known as liquid-crystal light valves (LCLV)—were first developed by Dr. Igor N. Kompanets at FIAN. The primary advantage of the device is that it requires only 10 to 100 volts to operate, as compared with 1,000 volts for the PRIZ and 4,000 to 7,000 volts for the PROM. Kompanets claimed that his LCLVs, fabricated from gallium arsenide, were capable of the edge enhancement and moving-target capability of the PRIZ, while offering increased resolution and sensitivity. [redacted] consistently specifies that Soviet LCLVs are faster than those manufactured in the United States.

A Soviet LCLV using an organic polymeric photoconductor reportedly was available for international sale in 1989. The Soviets claim this device is capable of storing 50 times more information than a similar device currently available in the United States. On the basis [redacted] and our analysis of open-literature publications, we assess the Soviets as having a five-year lead over the United States in LCLV development.

PRIM

In 1987 the Soviets produced a multilayer image converter referred to as the PRIM, which reportedly combines the resolution of the PROM with the best attributes of the PRIZ. [redacted] claim that it is an improvement over earlier Soviet SLMs.

EPOS

Introduced in early 1988, the newest Soviet SLM—the EPOS—is described by the Soviets in open literature as an innovative variation on the PRIZ device with a very specific application—the processing of periodic signals, such as those in aircraft radar and other electronic-warfare equipment. Whereas the PRIZ uses transparent electrodes, the EPOS uses opaque interdigital electrodes imprinted on the side of the crystal on which the "write-in" light is incident. The EPOS requires a biasing voltage of 2,500 volts and has aluminum electrodes deposited by photolithography techniques.

According to the Soviets, the geometry used for the EPOS device offers several advantages. First, if periodic signals are used as input, the diffraction efficiency of the device is independent of the spatial frequency of the input signal, up to input spatial frequencies of several hundred lines per millimeter. We believe the device would not be useful for image processing because of the opaque electrodes, but it may be highly effective for use in converting incoherent periodic signals to coherent ones. A possible military application would be in aircraft radar-warning gear and other electronic-warfare equipment.

Optical Memories

We believe that the largest contribution of optical systems to general purpose computing will come from parallel structures. Optical holographic memory offers the potential for parallel rather than serial data readout. This advantage probably is more important than advantages in memory size or information density. The Soviets openly acknowledged that a completely parallel information structure free from von Neumann limitations [1] with large storage capacity was not realizable as late as 1986. We see this acknowledgement as implying that practical Soviet optical structures continued to require parallel/serial data transfer and processing at that time

Holographic Memories

The Soviets reportedly have been producing holographic memory arrays for digital data using photographic film—the most common holographic storage medium—since 1972. Soviet applications of these systems include a holographic memory for storing patent data at the Nuclear Physics Institute in Gatchina, and the MIGOL-I document storage system fabricated by GOI in Leningrad. Although the Soviets have experienced high error rates in reading from holographic memories, we believe that they can develop error detection and correction techniques to provide adequate reliability. The holographic optical-storage applications receiving the greatest emphasis are document archival systems, but holographic systems fabricated by Soviet researchers at LFTI also have flown on Salyut-7, where holograms were formed in space and later video-transmitted to Earth.

In the early 1970s, L. A. Orlov and Yu. M. Popov of FIAN reportedly developed a holographic memory consisting of 1,000 by 1,000 elements, each element consisting of a 100 by 100 array of bits, for a total capacity of 10^{10} bits. Popov claimed it was possible to use several such holographic elements to build a computer with 10^{10} words of RAM and an access time of 50 nanoseconds. The report does not indicate whether these holographs are on film or implemented in a rewritable manner, which is necessary for use in a general purpose computer

[1] Performance limitations imposed by the sequential and address-oriented communications between the central processing unit and memory in a conventional computer.

[redacted] indicates that, by early 1989, FIAN had developed a holographic film sensitive to light in the gallium-arsenide (GaAs) laser wavelengths. The advantage of using this type of film is that GaAs diode lasers, when fabricated on an electro-optical integrated circuit, can be used as the light source. The result could be a miniaturized, rugged holographic-data storage system suitable for military applications. [redacted]

Organic Memory

The Soviets have a major R&D program for the development of photochromic materials from a synthesized variation of bacteriorhodopsin. Photochromic materials, unlike photographic materials, return to their normal state a short time after the excitation signal is removed and thus serve as dynamic memory arrays. Like the rhodopsin protein responsible for vision, bacteriorhodopsin stores energy through conformational changes when exposed to light of a certain frequency. Bacteriorhodopsin responds to light by pumping a proton across the cell membrane, creating an electrical potential difference. This protein also changes its optical absorption spectrum under stimulation of light. [redacted] the Soviets have been working since the early 1970s to develop analogs of this protein that exhibit long-term image retention, short read/write times, and high information densities.

Soviet researchers at the Biological Physics Institute in Pushchino have claimed in open-source literature that they have the best holographic-memory plane for Fourier space recording, using holographic techniques with a photochromic material called "Biochrom." Biochrom is a film based on the bacteriorhodopsin protein (from the micro-organism halobacterium halobium) incorporated into a polymer matrix and spin-coated over glass or silicon. Biochrom could be used for an optically based RAM or as a holographic memory element in an optical computer. Used in a holographic memory, Biochrom could demonstrate enhanced performance over that of conventional electronic memory. Holographic detectors have broad applications in optical computing, but speed and sensitivity limitations preclude general use of these elements as computer memory devices. Biochrom or a successor, however, has the potential to serve as the storage medium for optical holograms in a dynamically reconfigurable optical computer.

Residue Arithmetic for Optical Computing

In a residue (or modular) arithmetic system, a conventional positional notation number is represented by its set of remainders after division by a set of small prime numbers. A major advantage of this system is that the digits of a residue number can be operated on independently. Because no carries are generated, addition, subtraction, or multiplication of two numbers can be accomplished by parallel processes, and very high computational speeds may be realized. Residue arithmetic systems also lend themselves to table-lookup computer architecture. Residue arithmetic systems, however, do have difficulties in the operations of division, overflow detection, and magnitude comparisons of one number with another. We believe that the Soviets have exploited hybrid schemes in which some operations are performed in residue arithmetic and others in a positional notation system.

Soviet scientists and engineers have devoted much attention and research to residue arithmetic. Because of the high computation rates possibly using residue arithmetic for specific algorithms on large data sets, residue processors may be well suited for use in missiles, spacecraft, and aircraft. Open-source literature indicates that the Soviets have developed an entire class of special-purpose military digital residue processors, including a machine capable of 1.25 MIP (millions of instructions per second), Kristall computers (in 1965), 5- to 7-MIP machines (in 1974), and a 10-MIP machine (in 1975). The machines, manufactured at Institute NII-37 in Moscow, are currently in the Soviet operational inventory. We believe that the Soviets have overcome many of the disadvantages of residue number systems by focusing on special-purpose (military) systems and only a few algorithms. Although US optics engineers examined residue processors in the late 1970s, they were rejected in favor of electronic processors. US engineers, however, attempted to use optics for data processing, whereas the Soviets use optics only for the storage of tables. Western interest in residue arithmetic has been rekindled recently, but we believe the Soviets lead in this research by at least five years.

The Soviets also have explored positional systems with redundancy, where the carry operations in the calculation extend only to the next position. Although FIAN reportedly dropped the residue arithmetic approach in 1974, when development began on its control operation method (COM) for optical computing, research in residue arithmetic reportedly continues at other Soviet facilities. We believe that additional deployments of military systems based on residue-processing technology can be expected during the coming decade.

Optical and Hybrid Optoelectronic Architectures

Reconfigurable Architectures

Soviet researchers have been exceedingly active in the field of reconfigurable computer architectures. Standard general purpose computers seldom make full use of their potential computational power. Parallel-processor architectures, on the other hand, are difficult to program and use effectively for many classes of problems. A dynamically reconfigurable architecture would provide a better match between processes and processors. We assess Soviet prospects for implementation of a dynamically reconfigurable architecture in a general purpose computer using optical techniques as good, but not likely to occur before the year 2000.

The fabrication of an all-optical computer must await the development of many optical technologies. On the basis of open publications [redacted] however, we believe that the Soviets are developing theoretical architectures and operating algorithms for implementation in a future machine. We assess that the general design of a digital optical computer, as envisioned by the Soviets, most probably will use SLMs and be based on the COM developed at FIAN.

The Soviet COM is a variable operator approach, in which no hardware device will be dedicated to any particular operation. Assignments of operators to devices may be varied from one cycle of the computer to the next, resulting in greater flexibility and efficiency in a massively parallel processor system. In the Soviet COM-based machine, the processing operation an SLM performs will be controlled by a two-dimensional pattern or "picture operator" projected onto the SLM. In this architecture, the machine stores mathematical operators, rather than the results of calculations as is done in tabular processors

COM devices will operate with light as the energy mode to convey information through the computing circuit. By using different operator patterns, the COM-based machine will be programmed to perform different tasks with the same hardware architecture. The resulting machine will be a flexible, multipurpose fully optical computer. For example, by using a specific set of controlling images, such a machine could be used to do signal processing for a radar system. If improved algorithms were developed to do the processing, or if the hardware details of the radar system were improved, the signal processor could be reprogrammed by simply changing the control images

Control operators, according to the Soviets, will be stored as holographic arrays and projected onto the decision plane as required. We believe that the development by the Soviets of an efficient lasing cathode ray tube (LCRT) in 1987 may prove to be an excellent addressing device for the holographic arrays. Each electron-beam position on the LCRT would address a separate hologram on a plane array, with each hologram producing its own set of COM information.

Matrix Mathematics

The possibility of performing linear-algebraic operations optically (see figure 2) is a major motivation for the study of optical information processing. Linear algebra is computationally intensive, but many important calculations can be expressed as arithmetic operations on matrices. Although the accuracy provided by these processors is typically only 8 to 10 bits, it has been extended to 11 bits using binary encoding techniques with only a 5-bit, bit-dynamic range from the detector array. As of June 1985, Soviets at IAE in Novosibirsk had developed an optical-image accumulator and a compatible matrix-vector and matrix-matrix optical processor.

Tabular Processing

Open-source literature indicates that Soviet researchers have shown a significant interest in tabular methods of processing information since about 1970. Tabular processing methods involve the use of table-lookup techniques to perform the basic arithmetic operations of addition, subtraction, multiplication, and division. High-precision implementation of tabular processing requires a very large computer-memory capacity. This memory capacity is achievable by using optical/holographic memory technology

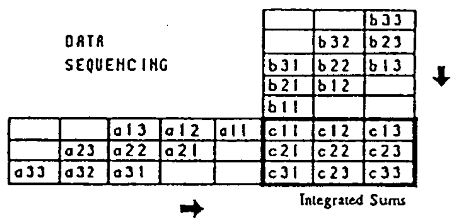
By using a holographic RAM with digital electronics, we believe that the Soviets can eventually build a fast computer that is a hybrid of digital electronics and optoelectronics. The results of mathematical operations in such a computer would be stored in tables in the holographic RAM. As the digital electronic central processor performed common mathematical operations, it would simply look up the result in the memory tables. Table-lookup processing is much faster than calculating the result of each operation and is used in some software on Western general purpose digital computers. The obvious limitation of the table-lookup method is that it requires an enormous amount of RAM. RAM, however, is abundant if the memory is holographic and is the basis of the tabular arithmetic unit, which would form the heart of a hybrid electronic/optoelectronic computer

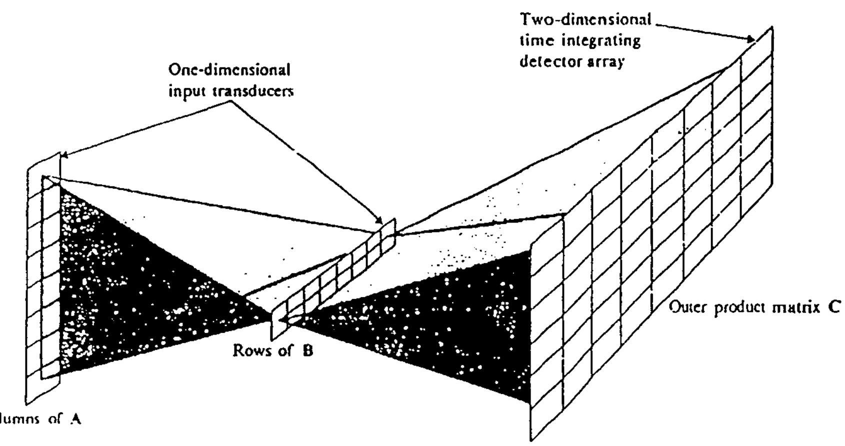
We assessed in 1985 that the Soviets would be in a position to produce such a hybrid computer in the 1987-92 time frame. Our assessment predicted that

Figure 2
Outer Product Decomposition Mathematics
Using One-Dimensional SLMs

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$$

$$= \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} & b_{13} \end{bmatrix} + \begin{bmatrix} a_{12} \\ a_{22} \\ a_{32} \end{bmatrix} \begin{bmatrix} b_{21} & b_{22} & b_{23} \end{bmatrix} + \begin{bmatrix} a_{13} \\ a_{23} \\ a_{33} \end{bmatrix} \begin{bmatrix} b_{31} & b_{32} & b_{33} \end{bmatrix}$$





An outer-product-based optical matrix-matrix multiplier using one-dimensional SLMs. Optical components not shown (for example, spherical-cylindrical lens combinations) spread light and image it in appropriate directions

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the hybrid computers—because of their improved ability to perform matrix calculations—would be useful in fields such as synthetic-aperture-radar (SAR) data processing, acoustic-array processing, and image processing. We believe this prediction remains accurate. As of mid-1989, however, we have no evidence of the production of such computers.

Optical Interconnections

We believe that optical interconnections are an area where the Soviets' advances may have a great effect on their general purpose computing systems. [redacted] but the Soviets discussed optical interconnections in open-source literature long before the subject became popular in the West.

Component interconnectivity is a critical issue in computer system design because of space requirements and time delay factors. Despite improving technology, currently no more than 200 to 300 electrical connections can be made, even to very-large-scale integrated (VLSI) circuits. Electrical conductors, moreover, also cannot be placed too close to each other, because the signals they carry generate magnetic fields that can induce currents in nearby conductors. The flat-plane geometry of integrated circuits is another limitation. Electrical connections can be made only at their edges. At very small sizes, optical connections are much easier to work with than electronic ones, because optical signals do not affect each other when their paths cross. Figure 3 shows examples of free-space optical interconnections being used to distribute focused and unfocused clock pulses throughout an entire electronic chip, thereby minimizing clock skew.[2]

[redacted] IAE in Novosibirsk has many optical interconnection elements under development. These elements are used to form interconnections between VLSI circuits—an area to which the Soviets have given much attention. The Soviet efforts are attempts to obtain optical communication between elements and functional assemblies of computational elements. [redacted] We believe these elements may be incorporated into holographic memory systems being fabricated at IAE.

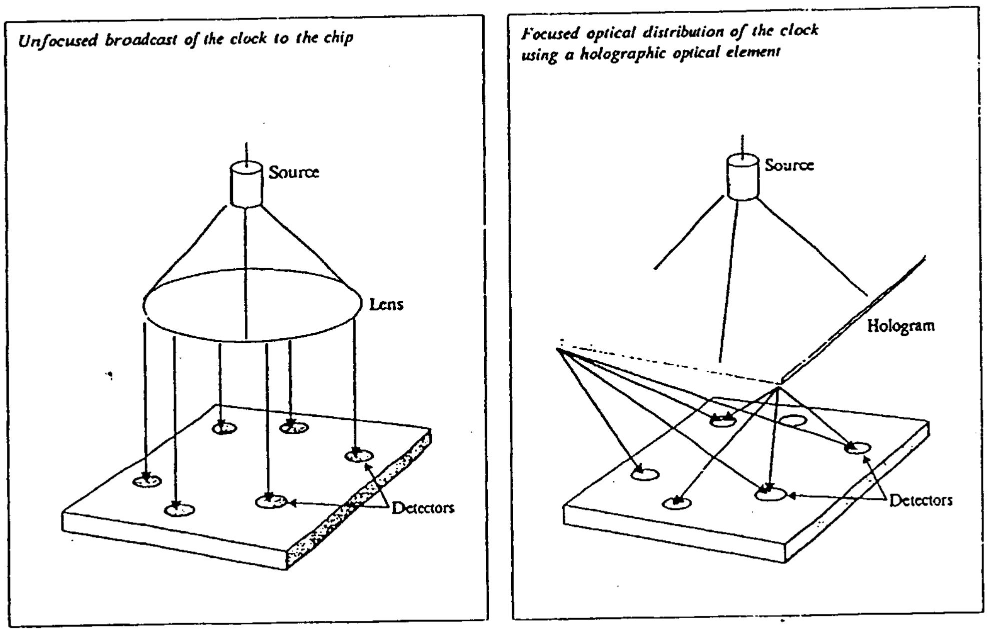
We believe that Soviet work on optical interconnection for general purpose computing systems may allow the combination of parallelism of processing elements and parallelism of interconnects. Because optical interconnects also can be made programmable, they can provide the basis for dynamically reconfigurable hardware. Dynamic machine reconfiguration tailors the complexity of the interconnection to the needs of the currently executing algorithm (see figure 4). For many interconnection applications, the use of holograms as deflection gratings would be greatly enhanced by the development of high-frame-rate SLMs. We believe that the Soviets are making great progress in this area. On the basis of technological factors, published Soviet work, [redacted] we believe that the successful development of dynamically variable interconnections would offer the Soviets the highest payoff of any of the emerging optical technologies.

Integrated Optics

The Soviets have a large research program in integrated optics, with major efforts under way to integrate optical sources, waveguides, detectors, lenses, gratings, modulators, and detectors on various substrates. The purpose of integrated optics is miniaturization, manufacturability, and reduced power consumption for a given processor. The integration of many optical components into a single device also offers the advantages of higher reliability and freedom from electronic and mechanical interference.

[2] Clock skew refers to the fact that different parts of the circuit or system receive the same state of the clock signal at different times because of varying electrical lengths of the different interconnection paths.

Figure 3
Free-Space Optical Interconnections



Free-space distribution of optical signal to multiple destinations in an optical circuit with minimum skew between the various signals.

Institutes reported to be key centers for integrated optics include FIAN, IOFAN, MEI, the Leningrad Polytechnical Institute, LFTI, and IRE. We believe that Soviet work on integrated optics will lead to feasibility demonstrations for some significant applications such as ultra-high-speed optical information processing, large bandwidth optical communications, and real-time electronic-warfare systems by the early 1990s

Prospects for Optical Computing

Despite documented advances in optical-component research, our technical assessment is that the Soviet optical computing effort remains at the early stages of what is effectively a new technology—optical engineering spurred by the development of materials and

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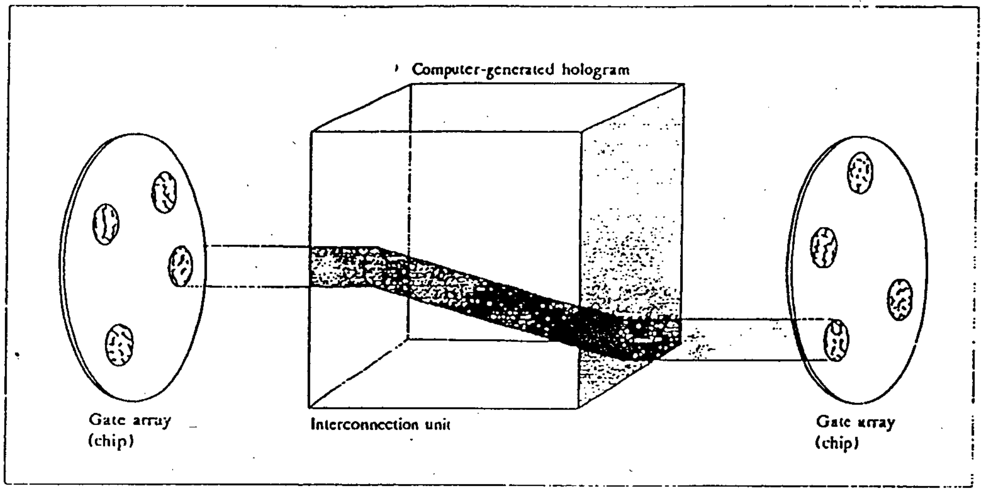
Figure 4
Chip-to-Chip Interconnection of an Optical Gate Array With a Computer-Generated Hologram



devices that take advantage of nonlinear optical phenomena. Although optics in general purpose computing systems have the potential to significantly increase computing speed through faster components, a faster carrier, and architectures that lend themselves to parallel systems, many problem areas need to be overcome. These include the lack of high-speed optical devices, interface problems between optical and electronic components, and the need for algorithms that will take advantage of the inherent parallelism of optical processing. On the basis of current Western levels of research, we expect continued Soviet progress in these areas to continue to outpace that of the West.

We believe that the Soviets will continue to use newly developed optical components and technologies in hybrid (optoelectronic) systems for special-purpose computer applications. Optical devices have been applied to Soviet radars, passive sensors, overhead imagers, and other elements of military systems. In addition, Soviet engineers have a demonstrated talent in the field of applications engineering. New developments in optoelectronic components are likely to appear in unexpected and unconventional Soviet military applications

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We believe that optics will permeate Soviet general purpose digital processors in an evolutionary rather than revolutionary manner, when there are distinct advantages to doing tasks optically (such as interconnects, clock distribution, and higher data flow rates). This gradual increase in optoelectronic hybridization of future computers will at some point result in what can most aptly be described as an optical computer, but not before the year 2000

Appendix A.

Key Technologies in Optical Computing

An all-optical general purpose computer will require the simultaneous maturity of several diverse technologies. The lack of success in one area, however, will limit the utility of any successful developments in the other research fields. Fabrication of optical components is expensive and time consuming, resulting in a limited number and variety of devices available for experimentation. Much of the current Soviet research is theoretical and conducted without access to actual devices. The devices that currently do exist, however, are proving extremely powerful in fulfilling specific functions as components in dedicated processors, such as signal and image processors.

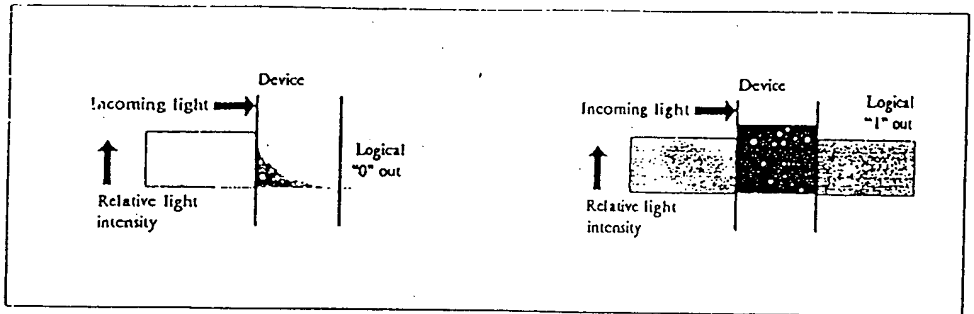
In designing a digital optical computer, one choice would be to develop an optical analog to the transistor (see figure 5) and produce a computer with an architecture similar to that used in current electronic computers. Work that has taken place in the field of optical bistability has been focused on developing just such an optical counterpart for the transistor. Despite the shorter switching times that may be possible with an optical transistor, there are problems as well as benefits with developing a pure optical computer-- particularly if the architecture of a current digital electronic computer is used. Interconnecting elements and components is a problem with any optical computer. With the interconnection complexity of electronic computer architectures, this problem is compounded. It also is not clear that optical transistors will ever lend themselves to the sort of VLSI fabrication that allows modern digital computers to be so compact, fast, and inexpensive (see inset), because the size of an optical transistor is limited by the wavelength of the light it uses. Therefore, we believe an alternative architecture designed purely for optical computers seems to be essential.

The core of any pure optical computer most likely will be an SLM—a combined short-term memory and processing unit - performing a function similar to that of a central processing unit in an electronic computer. Many different types of SLMs have been researched

Optical Switches

Advantages	*Disadvantages*
• *High Speed. Subpicosecond switching times are possible.*	• *High power is required for fast switching. This tends to create thermal problems unless highly transparent materials are used.*
• *Capability for parallel processing. For example, with a liquid-crystal bistable array, data arrays are a natural input form.*	• *Materials have not yet been identified that exhibit the ideal combination of properties required for these devices.*
• *Compatibility with optical fiber systems. Signals already in the form of light are easily transmitted between components.*	• *The minimum size of an optical switching element cannot be reduced below a volume of about the cube of the operating wavelength (λ^3). Theoretical and practical problems involved in waveguide and microresonator formation in λ^3 volumes are yet to be overcome.*
• *Large/broad bandwidth. For example, with a nonresident bistable optical device or a nonlinear interface, a large fraction of the visible light bandwidth can be used.*	• *There must be sufficient gain for one device to switch at least two succeeding devices, and preferably more.*
	• *Very steady bias beams are required.*
	• *Stability in chains of optically bistable elements is still a problem.*

Figure 5
An Optical Transistor



In certain materials, for particular ranges of wavelength and intensity of input light, the index of refraction becomes a function of the intensity. One possible implementation of an "optical transistor"—called an etalon—is a Fabry-Perot interferometer. This device consists of two parallel partially reflecting mirrors with a space (cavity) between them. Some portion of an incoming light beam is reflected by the first mirror. The remainder passes through the cavity to the second mirror, which reflects a portion of the light back into the cavity, and the rest is transmitted out of the device. Altering the optical length of the cavity by changing its physical length, its material, or the wavelength of the input light can suddenly and drastically change the amount of light transmitted by the device. If the cavity material changes its refractive index as a function of incident light intensity, the device can be adjusted to behave analogously to a transistor.

over the years, the most basic being photographic film. Drawbacks to the use of film are that the image is fixed, it cannot be erased or changed, and a new piece of film is needed for performing each operation. The most promising current technologies to produce optically or electrically controlled SLMs are the use of the linear electro-optical effect in crystals and the use of liquid-crystal displays. As viewed for use in digital computers, an SLM is a collection of discrete light gates in the form of a matrix, each of whose elements executes logic operations on 1 data bit. The transmission of each element is controlled by either an electrical or optical signal. Thus, the term "controlled transparency" also refers to SLMs. SLMs usually modulate the amount of light transmitted as a function of input light intensity. SLMs, however, can be designed to modulate the light as a function of an applied electric field, thus serving as the conversion interface between electronic and optical bit streams by placing the information to be processed into the optical system. SLMs, thus, can accept inputs, store and display outputs, and do calculations.

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Appendix B

Key Soviet Personnel Involved in Optical-Computing Research

Ginzburg, V. M., VNIIOFI, military applications of holography and radars

Bakhrakh, L. D., MNIIPS, radar and optical processing (holography)

Deryugin, L. N., MUDN, optics and missile work

Bakut, P. A., MEI, optical signal processing, pattern recognition

Gusev, O. B., LIAP, multichannel AO modulator

Grihev, A. Yu., processing radio array data with coherent optics

Voronin, Yu. M., beam shaping, processing requirements

Nakhmanson, G. S., acousto-optic processing for broadband 2D arrays

Vesepkina, N. A., multichannel AO devices

Grachev, A. A., optical processing of weather radar

Belousov, P. S., optical processing of radar images of sea ice

Kurochkin, A. P., MNIIPS, holographic computers

Turchin, V. I., MNIIPS, antenna patterns and holography

Basov, N. G., FIAN, administrator, tied to much optical-data-processing work

Popov, Yu. M., FIAN, PROM, holographic memory, digital optical processing

Kompanets, I. N., FIAN, PROM, liquid-crystal SLMs, optical computing, COM

Vasiliev, A. A., FIAN, liquid-crystal SLMs, Walsh and Hilbert transforms

Prokhorov, A. M., IOFAN, Bragg modulator, digital image processing

Petrov, M. P., LFTI, director of Shuvalov branch

Gurevich, S. B., LFTI, electro-optics materials research

Petrov, Yu. M., LFTI, head of group for optical computing

Khomenko, A. V., LFTI, PROM, PRIZ SLMs

Berezkin, V. I., LFTI, SLMs

Morozov, V. N., FIAN