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# THE DEVELOPMENT OF "OPTICAL COMPUTERS"

## A TASK FOR EUROPEAN RESEARCH.

In the framework of a European Community plan to stimulate European cooperation in science and technology, the Commission of the European Communities has put 1.8 million ECU into setting up an international grouping of 19 scientific research teams based at 18 different universities and research institutes with the purpose of developing an "optical computer".

"Optical computers" could leap over the technological barriers faced by our present-day systems. Instead of using electrons they would work with light, i.e. photons, which would be very much faster. Admittedly, today's supercomputers such as the Cray-1 already carry out thousands of millions of operations in a second, but their further development is coming up against foreseeable physical and technological barriers. According to our physicists' findings, these are likely to prove insurmountable. This is where "optical data processing" could come into its own and in all probalility make possible computer performances much better than can be achieved even with modern electronics. The electronic components in present-day designs of computer have two failings which are difficult to overcome: they are too slow and work only sequentially. Their switching speed cannot be improved beyond the thousand-millionths of a second, or nanosecond, range, and even with switching times as short as this they can process only one signal after another and therefore operate exclusively in sequantial mode.

The "optical components" which have so fare become known react about a thousand times faster, in the range down to billionths of a second, or picoseconds. Their shortest switching time so far observed is already around as little as a hundred femtoseconds, which amounts to a further reduction by the factor ten. More important than the switching time the manner of data processing. At the same time, hundreds or thousands of signals - we cannot yet say exactly - are processed simultaneously. This "parallel" procesing of individual signals increases the power of "optical computers" many times over. Nobody dares to predict how far this is likely to go, since basic research is only just in the process of developing and learning how to use the important optical components.

The key to such high performances by future computer generations is the use of the physical effect of "optical bistability". In this effect, various crystalline materials react to laser light with two precisely-defined and stable states : low-intensity light is absorbed or scarcely penetrates the crystals, but above a certain level of intensity the light passes through. The change is as quick as lightning. Optically bistable crystals "switch" from laser-opaque to laser-transparent and these two states characterize optical bistability. They thus correspond to the switching states "On" or "Off" of the electronically functioning transistors in our present computers, and can represent the two digits "0" and "1" of binary mathematics or the logic states "no" and "yes". Their reaction is analogous to that of the conventional electronic switching elements, but they are triggered by laser beams and thus follow the laws of optics.

## Are optical computers a practical proposition ?

None of the scientists participating today in the European Communities' joint project to investigate "optical bistability", which is part of the effort to stimulate research and development in Europe, is prepared to commit himself one way or the other. After all, it is precisely the purpose of the "European Optical Bistability Project" (EJOB) to examine the scientific foundations on which the construction of an optical computer would be based. It is still too early to assume that because the experiments have been successful a full-scale installation would work. It is not yet certain which materials are practical and durable enough. Mathematicians have only just begun to ponder the fundamentals of parallel data processing.

The results of the joint research which is now under way can form the basis for the optical computers of the future. There are numerous experiments which indicate feasibility. The European computer manufacturers are so far not commenting, since they cannot see what form the work would have to take and what techniques would have to be adopted. They probably have an idea that when optically bistable logic elements are put to use on an industrial scale the way to the "fifth generation" of computers will be clear.

The research results so far obtained indicate,however, that the optical computer is very similar in structure to the electronic one : optically bistable switches correspond to transistors, light beams correspond to pcb tracks. The similarity gives the scientists some hope that the optical computer will be relatively easy to develop, with electronic computers as a model.

For this reason, the eight European Laboratories and research teams working together on the EJOB project would like to have reached the stage by 1987, in two years' time, where they can discuss the posibility of constructing an "optical processor" as the main building-block. Until then the problems involved will have to be ironed out by conducting as many proving experiments as possible. This means finding answers or possible solutions to some important questions :

- what structure and "architecture" are integrated optical circuits to have ?
- which crystalline materials have the best optically bistable properties ?
- which lasers are suitable and with what wavelengths ?
- how fast should the optical logic elements work ?
- how and with what clock frequency are optical processors to work and in which beam intensity ?
- how can optical computers be connected with the "outside world" at data input and output ?

Until these and other more important problems of detail are solved, a start cannot be made with the design and construction of the first logic elements.

Some possible solutions are already making themselves apparent. The optimism with which the different teams are approaching their work to find solutions is also an indication that optical computers may very likely be in production in a few years. This is also bearing in mind that the new generation of computers represents a mixture of electronic and optically-functioning components. Such a "hybrid" computer is certainly within the realms of possibility : physicists are already developing numerous processes of opto-electronic states.

Furthermore, the optical bistability in the crystals studied corresponds to "electronholes" and free electrons, except that the triggering energy form is not electric currents but light beams. This is where the electronic and the optical systems are analogous. The physical similarity between the reactions shows that optical computers are not some futuristic dream but actually achievable now in the present state of physics research.

## What is optical bistability ?

Optical bistability can be understood purely and simply as an optical "switch" with two clearly distinguishable positions : "on" or "off". It works like any light switch, except that an optical bistable element does not switch the electric current on and off to control a light bulb but to regulate laser light directly. Instead of an electric current the light itself is "switched". The control parameters are different light intensities or different wavelengths. For it has become apparent that many crystal mixtures do not transmit light in a simple "linear" fashion, which means that contrary to our every day experience light does not penetrate crystal structures more as its intensity increases but there are crystals with "non-linear optical properties". From a certain light intensity upwards, crystals with non-linear optical properties suddenly allow much more light to pass through than would normally be expected. These sudden changes take place in fractions of a second, and it is on this that scientists base their hope that switching-times of billionths to trillionths of a second can be attained, a thousand to ten thousand times faster that the "fastest" of to-day's laboratory specimens of electronic gallium arsenide transistors can manage. It would be even faster than the "Josephson junctions" which operate in the supraconductive range at nearly 0° Kelvin. Athough optically bistable states were originally observed at about 70° K, corresponding to about -200°C, optical switching has already been achieved at ordinary room temperatures. So the optical computers of the future are unlikely to need any ultralow-temperature refrigeration units.

The fact that some crystals exhibit "non-linear" light transmission behaviour and show at least two typical stable states, i.e. bistability, had been predicted in 1969. The phenomenon was first detected in 1974 by scientists at BELL Laboratories in the United States, in sodium vapour. Five years later optical bistability was observed in gallium arsenide crystals, and almost simultaneously the Scottish researchers Eitan Abraham, Colin T. Seaton and S. Desmond Smith discovered non-linear refraction behaviour in indium antimonide crystals.

Since then many other semiconductor crystals which react in a non-linear way have been discovered, including, for example, cadmium sulphide, zinc selenide, zinc sulphide, copper chloride and mercury cadmium telluride. The search for crystals with a non-linear optical behaviour goes on unabated. Nowhere near all the crystals which come into consideration have been examined, and a "systematicsearch" programme has yet to be devised.

Scientists make a distinction between different kinds of optical bistability. In "dispersive optical bistability" there are light-intensity-dependent changes in the crystal's refractive index. In "absorptive bistability" the crystal's absorption index changes. Both types of bistability lead to stable states of light transmission, one at low light intensity and the other starting at a high level of light intensity. This behaviour can be pictured thus: crystals a few microns in size are opaque in weak light, but when the quantity of light reaches a certain level they suddenly become transparent. Other crystals react in the opposite manner in the case of "induced absorption": at first the proportion of transmitted light increases linearly with the rise in light intensity. Above a certain level of light intensity, however, they "switch" to a much lower level of lght transmission. Their behaviour is comparable to that of modern sunglasses, which "darken" in strong illumination.

To produce the two first-mentioned types of bistability, crystals with plane-parallel sides are used, some of which have to be provided with vapour-thin coatings. The external shape of the crystal has no effect on induced absorption.

The ways in which semiconductor crystals react depend on quantum-mechanical processes and electron movements and can already be described mathematically. Theoretical calculations often agree well with the results of laboratory experiments.

It is also important to know that materials which do not react in an "optically linear" fashion have much in common with electronic components and therefore show highly analogous switching functions. These include powers of amplification similar to those offered by transistors and high oscillations in the gigahertz range, which can be used for generating the clock frequencies of optical computers.

There are also "multi-stable" forms of reaction with three or more defined switching states. It is on this that hopes are based that one day, there will be computing with number bases other than binary. And these hopes offer the prospect that one day we may actually be building computers that can handle the decimal system, i.e. all the digits from 0 to 9.

## Design and mode of operation

The design of "integrated optical circuits" is much the same as that of electronic circuits. Conductors can to some extent be dispensed with altogether, or they are replaced by hair-thin fibres. The most convenient designs in principle are multilayer board structures. Besides a basic beam of light which can be split and reassembled by means of lenses, there will be other light beams, with a control function. The light will be guided by tiny mirrors, and it will make a little difference if two light-beams cross since the data signals they contain will hardly interfere with each other at all. This is likely to simplify design. Light behaves more "flexibly" than electrons. It oscillates in distinct frequencies and phases, and it has both wave character and corpuscular character. Light can therefore be used much more flexibly than electric current, and this will be to the benefit of the optical computer.

However, though the theory may be simple it is not so easy to put it into practice technically. There are many questions of detail which have to be solved and tested, and this is reflected in the assignment of duties within the EJOB project. For example, the search goes on for more materials with non-linear optical characteristics. New laser diodes have to be developed for infrared light. One conceivable method of data input might be to use the radiation pressure of laser light on moving mirrors. Data storage is also an important consideration in the design of optical processors. A possible mass storage medium might be fibre-optic image plates, the current designs of which convert light pulses into electrical pulses. It may be possible to dispense with such conversions, but then again it may happen that a number of the electronic solutions in comon use today will continue to be used. That would mean a fusion of optical computers with electronic computers to form "hybrid" computers.

## European research: neck-and-neck with the USA.

Although American physicists began to study the phenomena of optical bistability earlier than their European colleagues, the latter have now drawn more or less level. The reason is that the Scottish researchers under Desmond Smith have been able to persuade the Commission of the European Communities to adopt the EJOB project as an all-European activity.

Today there are 19 teams at 18 universities and research institutes closely collaborating on all questions to do with the optical computer. Each of these contributes the results of its own research towards attaining a common goal.

On the other hand the EJOB project bears no comparison with the promotion of research in the United States or Japan.

In the framework of EJOB the European Community is financing cooperation between European scientists to the tune of about 1.8 million ECU.

In the USA, research into optical bistability is concentrated in the University of Arizona, which is closely cooperating with industrial firms like BELL Laboratories, part of the former AT&T. A research centre founded specifically to develop optical computers has an annual budget of some $ 750 000, at least $ 150 000 being provided by the National Science Foundation and about $ 200 000 by the State of Arizona. Contributions from at least five interested industrial concerns and Department of Defense funding ensures that the scientists can work almost free of financial worries.

The Japanese research teams are no worse off, although relatively little information about their research results gets through to the West. The projects under way in Japan come under the heading "Fifth Generation Computer". In 1984 more than $ 22 million were spent just on preparatory research for the "sequential inference machine". Experts estimate that for the current ten-year programme up to 1991 more than $ 100 million are available. Coordination of the research and development work is in the hands of the Japanese "Institute for New Generation Computer Technology" (ICOT), which receives its finance from the Ministry for International Trade and Industry (MITI).

It is not easy for Western scientists to see to what extent the Japanese are concerning themselves with projects to do with the construction of optical computers, but since Japanese researchers have much experience using gallium arsenide and have already announced switching times in the picosecond range, it is obvious that they are also studying optical bistability. But they are concentrating on "uniting" optical and electronic characteristics of semiconductor crystals in order to develop "hybrid"computers.

From the point of view of the European research teams it would be useful if, as in the USA, European computer manufacturers would begin to take an interest in the "optical computer", since there is a gap here which could easily be filled.