Optical computers

A classical finite state machine

Alan Miller

PROTOTYPE optical logic devices, which can perform the equivalent functions to transistors in electronic computers, have been available for the past few years[1] but their potential for carrying out useful signal processing and computational tasks is yet to be fully assessed (see my recent News and Views article[2]). Some comparisons can be made with digital electronic computers, which are now highly advanced machines comprising many logic gates (millions in large electronic systems), each of which must satisfy well-defined performance criteria. A paper on page 27 of this issue[3] by Desmond Smith and co-workers from Heriot-Watt University, Edinburgh, shows that optical logic devices can fulfill the requirements of gain, cascadability and restoring logic by cascading all-optical bistable devices in loop circuits while demonstrating the principle of the 'classical finite state machine'.

It is already common to superimpose information or data onto a laser beam for communication, storage or output purposes, but the data at either end of the storage or communication are still processed electronically. The challenge now being faced is how to extend the role of optics to the practical processing of data while they are still in the form of light.

Light photons have essentially complementary properties to electrons. Basic to these is the fact that electrons affect each other even at a distance, whereas light beams pass through each other unperturbed in the absence of any nonlinear interaction. This makes light a potentially useful, low cross-talk, high bandwidth means of interconnecting many devices in parallel. When one adds to these properties the fact that timing of optical pulses after propagation in free space or along fibres can be defined very precisely and that optical interactions with nonlinear materials can be extremely fast, light offers advantages precisely in the areas where the future high-speed performance of electronic computers based on small-scale integrated devices is going to be limited. Although faster electronic switching devices can be realized, their use is restricted by connectivity limitations (the number of gates or circuit units which can be interconnected with wires either on a chip or between chips), interconnection bandwidth (the data transfer rate that these wires can handle) and clock skew (the uncertainty in timing the arrival of electrical signals at different parts of a computer).

Alan Huang of AT&T Bell Laboratories has discussed[4] how light could be used to enhance computing power and, in particular, has suggested the use of optics to overcome the 'Von Neumann bottleneck' of electronic computers. In a conventional computer, for instance, there are fewer interconnections between the logic unit (central processor) and the memory than there are memory locations, so signals sent to the memory must be accompanied by addresses. Also there is a single return line for the data so the data are processed serially. The overall performance is therefore degraded when compared with the classical finite state machine in which all storage elements are accessed in parallel without the need for addresses. By using parallel beams of laser light, optics is clearly well suited to the latter type of architecture, but first it is necessary to create optical memory and logic devices that can offer cascadability and restorable logic. In other words, the output of one device must be able to act as input to other similar devices while maintaining standard signals as logic levels to prevent the deterioration of information during long series of operations.

The Edinburgh group[3] has developed nonlinear optical devices as three-port bistable logic elements. In other words, these are devices with two inputs and one output; for a given optical input power from a 'hold' laser beam (effectively the power supply to the device) there exist two possible transmission (or in some cases reflection) levels. The second input, a 'control' beam, can switch the device between these low and high transmission states. While the hold beam is on, it maintains the current logic level but the device is reset by interrupting this beam. These devices can function as short-term memory elements or logic gates. Signal gain between the control beam and the output is essential so that the output of one device can switch one or more subsequent devices. This demands good contrast between the low and high output levels. Restoring logic is simply achieved using control beams which are incident at an angle to the hold beam so that the output consists of only the transmitted or reflected hold beam which can be set at a standard level for all devices.

The optical circuits demonstrated use thin multilayer coatings (optical filters) deposited on flat glass plates and exhibit optical bistability when a laser beam is focused to a small spot on the plate at a specific angle of incidence. Three of these glass plates are positioned such that green beams from an argon-ion laser can be passed from one plate to the next around in a loop using appropriate mirrors and lenses. Each plate has a hold beam incident from outside the loop to supply the required power. Because the transit time of light around the loop (about 10^{-9} seconds) is faster than the response time of present devices, the authors used a 'lock and clock' cycling system. Pulsing the input beams in the correct sequence, the bistable devices can be powered and reset so as to pass signals from device to device around the loop while carrying out a logic operation at each stage. Small numbers of parallel beams generated using holograms show that parallel arrays of data can be simultaneously and independently processed by the loop. If scaled up, these concepts could thus provide parallel processors with the relatively slow response of individual elements being compensated for by the ability to process large numbers of channels in parallel.

The new results of Smith's group[3] demonstrate that repetitive manipulation and processing of parallel data streams without signal degradation is possible using all-optical devices. A processing stage (containing the computer program) would convert this into a computational machine appropriate to applications which require parallel processing of data. One example is image processing, presently carried out using computers working serially despite the fact that both the input image and the output display are in a two-dimensional form.

Much further work is required on optimization of optical elements in terms of power, speed, reliability and so on, but these devices could soon provide test-beds for new ideas on computational algorithms using architectures appropriate to large-array parallel processing. One might visualize, for instance, 1 cm^2 plates which it is reasonable to assume could dissipate 10 W of laser power. This would allow an array of 10^5 bistable elements on each plate if the holding power per element could be reduced, as projected[3], to 100 μW. The computing power of such devices cannot properly be calculated, however, until architectural ideas for using such a massive degree of parallellism are better developed. Some comparison may be possible here with neural networks in the brain, and their various hardware analogues. Thus, this new optical technology should not be viewed as a competitor for electronics but rather as an additional degree of freedom. ☐

1. Gibbs, H.M. *Optical Bistability: Controlling Light with Light* (Academic, Orlando, 1985).
2. Miller, A. *Nature* **323**, 13 – 14 (1986).
3. Smith, S.D., Walker, A.C., Tooley, F.A.P. & Wherrett, B.S. *Nature* **325**, 27 – 31 (1987).
4. Huang, A. *Phil. Trans. R. Soc.* **A313**, 205 – 211 (1985).

Alan Miller is at the Royal Signals and Radar Establishment, Malvern, Worcestershire WR14 3PS, UK.