# 4 decades of optical information processing

## 1990 Ives Medal Address

The fact that my title mentions four decades of optical information processing should not be taken to mean that I personally participated in all of those decades. In fact, I joined the field of optics by pure accident in 1963, after a Ph.D. in the field of radar signal processing. I participated in the last three of the four decades, and I was close enough to the first decade to have been influenced by it extensively. The 1960s were exciting times. The HeNe laser had just become commercially available. New ideas were surfacing in the field of holography that had great appeal to one trained in systems theory. From the perspective of academia, Ph.D. thesis topics were plentiful.

I would like to discuss these four decades with you, emphasizing what I believe to have been the most important developments, reflecting on both the accomplishments and the disappointments.

The names I've given to these decades are "simple Fourier processing" for the '50s, (the word "simple" is not meant to belittle the accomplishments of those working during these years, only to indicate that more complex things were to follow), "complex Fourier processing" for the '60s, "matrix processing" for the '70s. For the '80s I need three names: optical computing, neural computing, and optical interconnections. The fact that three names are needed is an indication that the field has become richer and more diverse in the last decade.

Of course, the ideas developed in one decade spilled over into later decades as well, so there are really not such hard divisions between these decades. Nonetheless, this categorization is a useful generalization.

### Simple Fourier processing: The 1950s

Certainly the most fundamental optical signal processing system is the simple Fourier transform arrangement shown in Figure 1. Data entered in the form of a two-dimensional transparency is Fourier analyzed by the system, and the power spectrum of the object is directly measurable. Large space bandwidth products can be handled. Objects are generally limited to being positive and real. While the Fourier transforming properties of positive lenses were used before the decade of the '50s, it was during that decade that the real significance of this operation became most evident.

These two-dimensional Fourier transforming properties of lenses can then be combined to yield the spatial filtering system shown in Figure 2. The 2-D spectrum of the object can then be intentionally manipulated by means of a focal plane filter.

To give some kind of idea about the interests in those days, I have listed four references from that decade.[1-4] Clearly, an appreciation for the Fourier approach in coherent optics developed in the early '50s, and experiments with filtering problems came in the mid-'50s. Initial applications were to image contrast enhancement. Later, applications to signal detection were emphasized. The number of individuals working in this field of research was small in the first 10 years.

### Complex Fourier processing: The 1960s

Late in the '50s an interest grew at the University of Michigan in the use of optics for radar signal processing, spearheaded by Cutrona, Leith, and others.[5] While some of this basic work was actually done in the late '50s, it was not published in the open literature until the early '60s. At that time, the field had three main branches: synthetic aperture radar signal processing, matched filtering for pattern recognition, and acousto-optic signal processing. I will briefly

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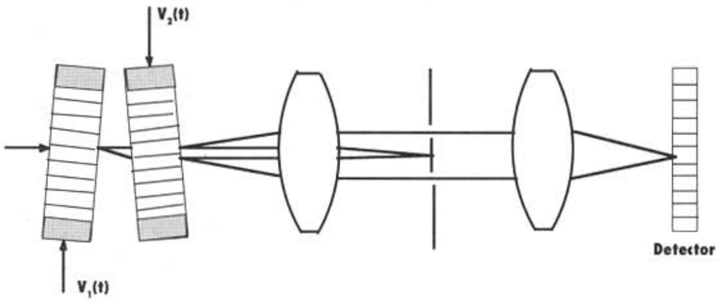

Figure 1. Fourier transformations by means of coherent optics.

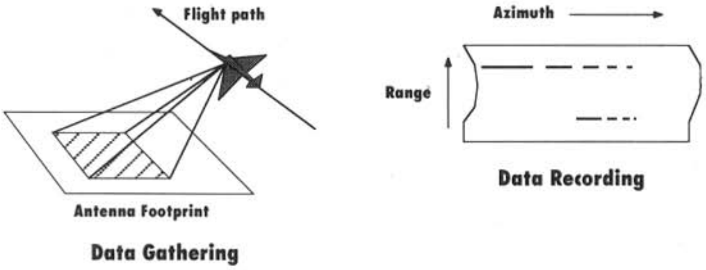

Figure 2. Spatial filtering by means of a succession of Fourier transforms.

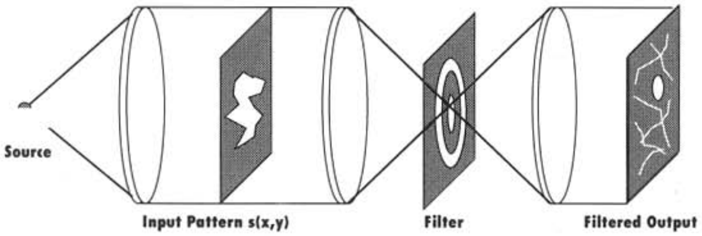

Figure 3. Synthetic aperture optics - data gathering and recording.

discuss each of these branches separately.

The synthetic aperture problem is extremely complex[6] and I will not dwell on it here. It suffices to say that from coherent measurements of reflected microwave radiation, emitted and detected from a flying aircraft, one attempts to reconstruct a map of the radar reflectivity of the terrain over which the plane has flown. As indicated in Figure 3, scattering points on the ground generate one-dimensional zone-plate structures on film, which is used as the storage medium on the aircraft. The focal lengths of these zone plates are a linear function of the range of the scatterers from the aircraft; as a consequence, the range and azimuth image planes do not coincide.

To reconstruct a map of the reflectivity of the terrain, it is necessary to bring the range and azimuth image planes into coincidence. The earliest optical processing system did so with the help of an unusual optical element— an axicon or a conical lens— as shown in Figure 4. Film was moved simultaneously through the input plane and past an output slit.

During the late '60s, a much more sophisticated processor was developed at Michigan— the titled plane processor. The results were first published in the early '70s.[7] The need for an output slit was eliminated. This system may still represent the most sophisticated optical processing system ever built. While digital techniques have now displaced a great deal of optical processing in this field, the methods were extremely useful in their time. In addition, the basic concepts had enormous intellectual impact. It would be fair to say that the modern field of holography stemmed from this effort on optical signal processing.

There grew out of synthetic aperture radar processing a realization that the holographic techniques developed for that problem could be applied more generally to the spatial filtering of images. In 1964 Vander Lugt published his classic paper on optical matched filtering with holographic spatial filters.[8] This idea has been one of the most influential in the field. By incorporating a tilted reference beam while recording a filter, both Fourier amplitude and phase information could be captured and used in a truly complex filter. When such a holographic filter is used in a Fourier type processor, very general filters can be realized. In particular, it is possible to construct matched filters designed to detect the presence of objects of known structure in an image field.

The influence of the holographic matched filter has extended from the 1960s to today. An extremely compact and solid optical matched filtering system was built jointly by Perkin-Elmer and the Jet Propulsion Laboratory with funding from the Army Missile Command. The entire system can be held in the palm of one's hand. The solid structure removes the need to have a person with a Ph.D. in optics constantly adjusting the alignment of the system. This system represents the pinnacle of this particular approach to pattern recognition—at least so far.

Looking back over all of these years of effort in this area, the one major disappointment is that these techniques to date have no commercial applications. Companies have risen and fallen in attempts to commercialize this technology. The lack of success probably stems in part from the inflexible nature of the matched filter approach to pattern recognition.

The third thrust of the '60s was acousto-optic signal processing. As illustrated in Figure 5, the simple Fourier transforming properties of optics are applied to the spectral analysis of electrical signals, entered into the optical

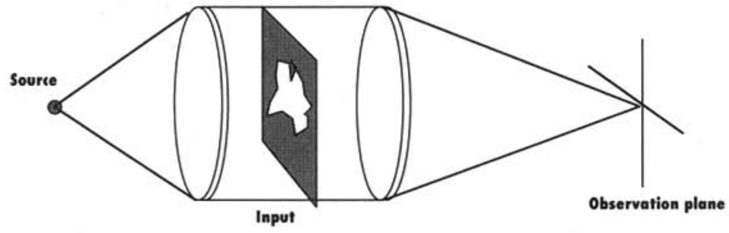

**Figure 4. Processing synthetic aperture radar data.**

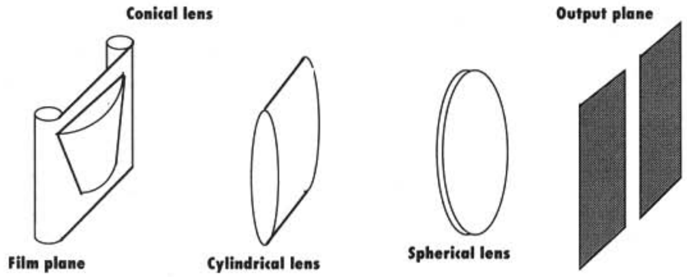

**Figure 5. Acousto-optic spectrum analysis.**

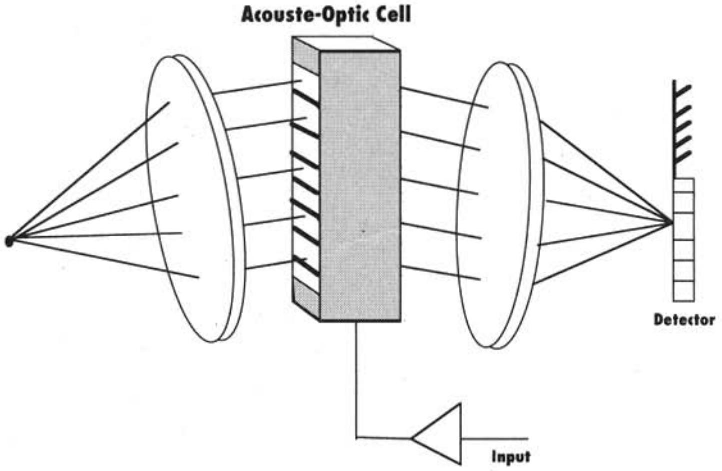

**Figure 6. The space-integrating correlator.**

system through acousto-optics (for basic references, see Refs. 9 and 10. Early work focused on devices that utilized the Raman Nath regime of diffraction. The work spilled over into later decades, where the frequencies were sufficiently high and the materials used such that Bragg diffraction was the dominant phenomenon. Great success was achieved in the application of these systems to military reconnaissance problems. Alas, no commercial applications have been found here either.

The use of acousto-optic techniques for signal input was extended to correlators for detecting known radar or communication signals in the presence of noise. Figure 6 shows one such approach—the space integrating correlator—in which the correlation integral is performed over space and values of the correlation integral with different delays emerge continuously at the output.

Tails extending into the '70s led to the concept of the time-integrating correlator, patented by Montgomery in the early '70s,[11] and further developed by Sprague and Koliopolis in the later 70's.[12] As illustrated in Figure 7, the correlation integral is performed over time using time integrating detectors and time delay varies across the detector array. The maximum length of integration is no longer limited by the time delay of the Bragg cell.

### Matrix processing: The 1970s.

The 1970s were certainly the years of matrix processing. Attention turned away from the continuous operations of the Fourier-based processor to discrete operations associated with matrix algebra.

The granddaddy of this generation of processors was the serial matrix vector multiplier invented by Bocker and Bromley, reported in 1974.[13,14] As illustrated in Figure 8, data was input in the form of a discrete pulse train, each pulse having an amplitude representing one analog element of an input vector. The elements of the matrix are stored in a mask, which can be fixed or changeable. The sums required in the matrix-vector product are performed by means of charge integration on a CCD array. A critical column of charge is passed to the right, in synchronism with the emitted light pulses, adding new contributions at each location. When that column reaches the far right of the detector array, it contains charge packets of magnitudes that represent the elements of the output vector.

In the late '70s, I was fortunate to conceive of a parallel version of this processor that had much greater potential for speed.[15] In this case, the input vector is entered on an array of light sources, as shown in Figure 9. The matrix mask is the same as for the previous system. Optical addition is performed and the components of the output vector are detected on a 1D detector array. Extremely high throughputs are possible. In the '80s, this architecture was used to implement early neural networks, as we shall see, and has been the basis for a series of fiber optic crossbar switches. Psaltis, Casasent, and Carlotto also used it to solve systems of linear equations through an iterative procedure.[16]

Work on matrix-oriented optical processors continued into the '80s. Particularly important contributions were the outer-product processor,[17] the systolic matrix-vector processor,[18] and the SAOBIC processor.[19]

### Optical computing: The 1980s

In the 1980s, there were three different branches to the field. The first considered here is optical interconnections, in which we attempt to use optics to solve interconnect problems within otherwise electronic digital computers. The second is optical neural networks, in which the interconnectivity advantages of optics are applied to constructing systems that are based on models of biological systems. The third is optical computing, in which we use optical gates and optical wiring to construct an all-optical digital computer.

Turning first to optical interconnects, the earliest work in this field can be traced back to the beginning of the 1980s. Notable among these efforts was the Dialog.H computer in Japan, which used an optical bus to connect its multiple processors. The idea was published in 1981 and an experimental system was reported in 1983.[20]

In 1984, the first general proposal for the use of optics in solving electronic interconnect problems was published, and I was fortunate to have been a part of that effort.[21] We have come a long way since that time.

Some of the significant milestones in optical interconnections were mentioned in a recent article in *Optics & Photonics News*.[22] They include the development of a high speed optical backplane for a switching computer by Bell Northern Research, the development of polymer waveguide technology compatible with electronic boards by several organizations, the exploration of optical interconnects for the connection machine by Honeywell and Thinking Machines Inc., the demonstration of 300 MHz clock distribution to 1024 nodes with 12 psec of jitter by Bellcore, the development of complex GaAs chips interfaced to high speed fibers by IBM, and the demonstration of high efficiency interconnect link at MIT Lincoln Labs.

Turning to neural networks, in the mid-1980s, the so-called Hopfield model of a neural system was implemented optically.[23] The system uses a parallel matrix-vector multiplier with feedback through a nonlinearity. Associative memories have dominated the interest in applications of this type of system.

More recent work on neural networks has focused on photorefractive crystals. The development of novelty filters[24] and multilayer trainable neural net architectures[25] are particularly noteworthy.

We turn lastly to the subject of all-optical digital computing. This has certainly been the subject that has fired the imagination of the press most effectively. Significant efforts in this area have been limited to a few institutions. In early 1990, two different groups at AT&T reported the successful operation of computing and switching structures based on arrays of interconnected S-SEED devices. To date, these systems have not been run at high enough speeds to be competitive with electronics, but there is much potential for improvement. The device technology developed for this purpose has been fascinating and exciting in its own right. Figure 10 shows a general diagram of the AT&T Naperville switching system, which is based on S-SEED devices and crossover network architecture.[26] As you can see, the system is extremely complex. Tremendous skill was needed to put it together properly. One can speculate on whether systems like this will have an impact in the future on general purpose digital computing. I do feel certain that the technology will find real application in the communications business, in special purpose processors, or switches of some kind.

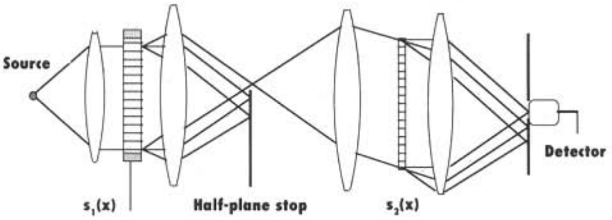

Figure 7. The time integrating correlator.

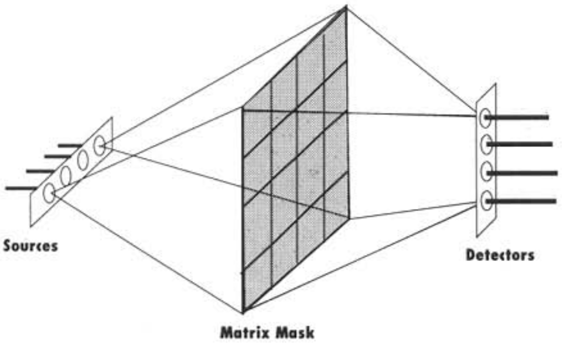

Figure 8. The serial matrix-vector multiplier.

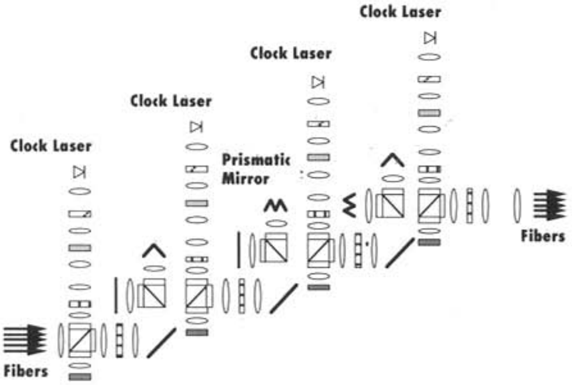

Figure 9. The parallel matrix-vector multiplier.

### The 1990s: What's to come?

In the 1990s, I believe that there will be very significant progress in bringing photonics into electronic computers, primarily for the solution of interconnect problems. I predict that optics will be employed at least at the backplane level in several high-performance machines. I also predict that leadership in this field will shift away from the U.S. to Europe and Japan, where there will be a greater willingness to try new technology when the results cannot be fully predicted in advance.

Throughout the '90s, I believe that optical neural networks will remain one of the most exciting subjects for research in this field. However, I also predict that during this timeframe there will be no commercial application of this technology, due to rapid advances in electronic solutions.

The field of digital optical computing is the most difficult to make predictions about. Difficulty arises partly from the dynamic state of device technology in this exciting field. Certain milestones will be necessary before the end of the decade if the field is to remain alive. Minimum accomplishments should include the interconnection of several arrays of >1000 gates clocked at speeds of at least 100 Mhz. Of these requirements, the most difficult will be the simultaneous interconnection of more than 1000 gates in several arrays. If this goal is not met, then the future is not bright. However, lest I sound too pessimistic, I believe that the goals *will* be met. Furthermore, I believe that during the decade, several applications far simpler than a general purpose digital computer will be found (the switching computer discussed above is one example) and that optics will be found to have advantages over electronics in certain applications of these systems.

This has been a tremendously exciting field to be part of the last 30 years or so. I expect that it will remain a vital and important part of optics for many years to come.

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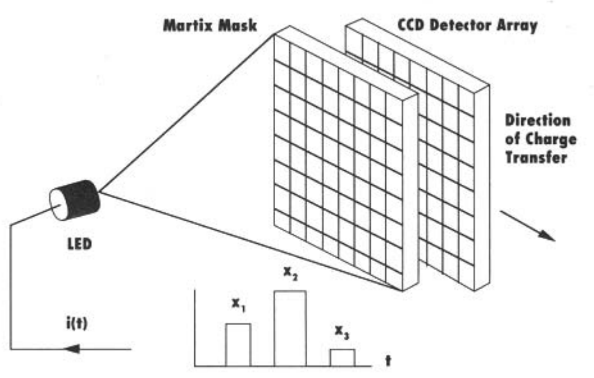

**Figure 10. The AT&T digital switching computer.**

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