ISSN 2229-5518

# The Evolution of Optical Computing- Past, Present & Future

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**Abstract**— this paper gives a brief description about the evolution of Optical Computing Optical computing generated a lot of enthusiasm in the sixties with major breakthroughs opening a large number of perspectives.

**Index Terms**— .SLM, biophotonics, nanophotonics, CGHs

## 1 INTRODUCTION

Optical computing has been one of the most important areas of research for the past sixty years. This paper gives a brief historical review of the life of optical computing from the early days until today. The interest in Optical computing started in the sixties with major breakthroughs opening a large number of perspectives. The period after 1980's could be called the golden age as various new inventions and applications of optical computing were developed. Even today the optical computing is an important area of research and has evolved and its results benefit to new research topics such as nano optics, bio photonics, or communication systems.

Optical computing has been of great importance over a long period of time and hence it is interesting to study its evolution. A debate about using optics in computers has been since the beginning whereas there was no doubt about the potential and the future of electronics. Caulfield in 1998 wrote a paper on the perspectives in optical computing [7] where he discusses this competition between optics and electronics and shows that there were three phases, first "*ignorance and underestimation*" of electronics then "*awakening and fear inferiority*" and now "*realistic acceptance that optical computing and electronics are eternal partners*".

The purpose of this paper is to study the evolution of optical computing from the origin until today. This study will lead us to understand the beginning of Optical computing which slowed down after a great start until the mid-80's, after which various applications of optical computing have been developed.

Section 2 presents the Fundamentals of optical information processing, Section 3 gives a historical review of the research until 1980 and Section 4 describes the research activity from 1980 to 2004. Section 5 shows the evolution of the domain until today.

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## 2. Basics of Optical Information Processing

Optical information processing is based on the idea of processing the information at high-data rate using all the properties of speed and parallelism of the light. The information may be in the form of an optical signal or image. One of the most highlighted advantage of optical processing compared to electronic processing computers was inherent parallel processing Hence, optics has an important potential for processing large amount of data in real time. The basis of optical computing is the Fourier transform of a lens. When using coherent light, the Fourier transform of a 2D transparency located in the front focal plane of a lens, is performed in its back focal plane . The exact Fourier transform with the amplitude and the phase is computed in an analog way by the lens.

### 2.1. Optical Processor Architecture

The processor is the combination of three planes: the input plane, the processing plane, and the output plane.

The data to be processed are displayed in the input plane. A Spatial Light Modulator (SLM) is used to perform an electrical to optical conversion, in this plane for most of the time. The input signal can be 1D or 2D. A 1D input signal uses an acousto-optic cell and 2D SLMs for 2D signals. The processing plane can be composed of lenses, holograms (optically recorded or computer generated) or nonlinear components. This is the heart of the processing, and in most optical processors, this part can be performed at the speed of the light.

A photo detector array, A photo detector, or a camera com- poses the output plane where the results of the processing are detected.

**2.2. Optical Processors Classical Architectures**. Real-time pattern recognition was seen as one of the most promising application of optical processors in the beginning and the following two architectures of optical correlators were proposed because of them. Figure 2(a) shows the 4-f as the distance between the input plane and the output plane is four times the focal length of the lenses. It was the basic correlators. This very simple architecture is based on the work of Maréchal and Croce [9] in 1953 on spatial filtering and was developed during the following years by several authors [10, 11].

The input scene is displayed in the input plane which Fourier transform is performed by Lens 1. The complex conjugated of the Fourier transform of the reference is placed in the Fourier plane and therefore multiplied by the Fourier transform of the input scene. Lens 2 performs a second Fourier transform that gives in the output plane
the correlation between the input scene and the reference.

Implementing a complex filter with the Fourier transform of the reference was the main challenge of this set-up, and Vander Lugt proposed in 1964 to use a Fourier hologram of the reference as a filter [12]. Figures 2(b) and 2(c) show respectively, the output correlation peak for an autocorrelation when the correlation filter is a matched filter and when it is a phase only filter [13].

In 1966, Weaver and Goodman [14] presented optical correlator architecture, the joint transform correlator (JTC) that is represented by Figure 3(a). The two images, the reference $r(x, y)$ and the scene $s(x, y)$ are placed side by side in the input plane that is Fourier transformed by the first lens. The intensity of the joint spectrum is detected and then its Fourier transform is performed. This second Fourier transform is composed by several terms including the cross correlations between the scene and the reference. Figures 2 and 3 represent coherent



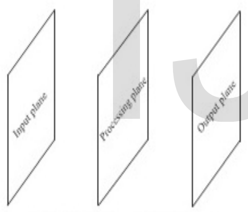


Figure 1: Architecture of an optical processor

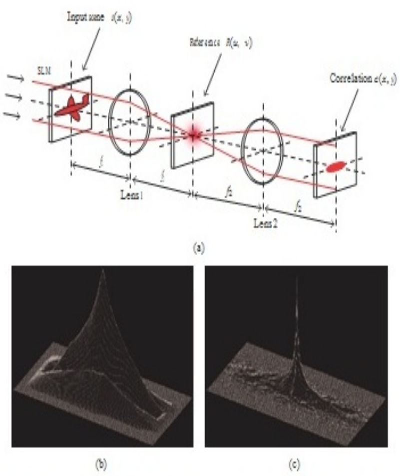


Figure 2: Basic 4-f correlator: (a) Optical setup. (b) Autocorrelation peak for a matched filter (c) Autocorrelation peak for a phase only filter.

Optical processors. Incoherent optical processors were also proposed: the infor- mation is not carried by complex wave amplitudes but by wave intensities. Incoherent processors are not sensitive to the phase variations in the input plane and they exhibit no coherent noise. However, the nonnegative real value of the information imposes to use various tricks for the implementation of some signal processing applications [15, 16].

## 3. The Rise of Optical Computing (1945–1980)

Since the fifties Information optics is a recognized branch of optics. However, historically, the knife-edge test by Foucault in 1859 [20] can originate the optical information processing. Other contributors can be noted such as Abbe in 1873 that developed the theory of image formation in the microscope, or Zernike who presented in 1934 the phase contrast filter. In 1946, Duffieux made a major contribution with the publication of a book on the use of the Fourier methods in optics.

Optical computing is based on a new way of analyzing the optical problems; indeed, the concepts of communications and information theory constitute the basis of optical information processing.

### 3.1 The Future of Optical Information Processing as Seen in 1962.

In order to understand the evolution of optical computing, it is enlightening to see the topics of discussions in the early sixties. For example, in October 1962, a "Symposium on Optical Processing of Information" was held in Washington DC, cosponsored by the Information System
Branch of the Office of Naval Research and the American Optical Company. About 425 scientists attended this meeting
and Proceedings were published [52]. The preface of the proceedings shows that the purpose of this symposium was to bring together researchers from the fields of optics and information processing. The authors of the preface recognize that optics can be used for special-purpose optical processors in the fields of pattern recognition, character recognition, and information retrieval, since optical systems offer in these cases the ability to process many items in parallel.

It is interesting to list the topics of the symposium: optical effects (spatial filtering, laser, fiber optics, modulation and control, detection, electrolumi-nescent, and photoconductive) and data processing (needs, biological systems, bionic systems, photographic, logical systems, optical storage systems, and pattern recognition). It can be noted, that one of the speakers, Teager from MIT, pointed out that for him the development of an optical general-purpose computer was highly premature because the optical technology was not ready in order to compete with the electronic computers. For him, the optical computers will have a different form than electronic computers; they will be more parallel.

## 4. The Golden Era of Optical Computing (1980–2004)

The time between 1980 and 2004 could be called the optical computing golden age. There was a lot of encouragement in the field, the future looked very bright, and there was monetary help for the research effort was also available worldwide.

The journals had frequently a special issue on the topics and Applied Optics had every 10th of month an issue entitled "Information Processing". The research was very fruitful in all the domains of optical information processing including theoretical work on algorithms, analog and digital computing, linear and non- linear computing. Optical correlators for real applications were even commercialized. However, around 2000, we could feel the decline in the subject. The reasons are multiple, but the evolution of digital computers in term of performance, power and also flexibility can be pointed out. They are also very easy to use even for a non- specialist.

It is impossible to list here all the work carried out in the domain from 1980 to 2004. Several books give the state of the art of the domain at the time of their publication [4, 6]. In the following, we shall study only some aspects of the research during this period, and we apologize for some important results that may be missing. The sole purpose is to give to reader an idea of the evolution of the domain during this period.

### 4.1. From Computer Generated Holograms to Diffractive optical elements

CGHs are important components for optical processing since they can process the information. The first CGHs were cell-oriented since they were well adapted to the power of the computers with a small memory capacity. In the eighties, the technological landscape evolved, more powerful computers with a larger memory capacity were available, and therefore new encoding methods, the point-oriented methods, were developed in order to achieve high quality and high diffraction efficiency optical reconstructions of the CGHs.First, the error diffusion algorithm, used for printing

Applications, was adapted to encode CGHs where it was possible to separate the noise from the desired pattern in the reconstruction plane . Then, iterative algorithms were proposed and the best known are the Direct Binary Search (DBS) algorithm proposed by Seldowitz et al. in a reconstruction with a high signal to noise ratio and high diffraction efficiency especially in the case of pure phase CGHs.

Later some refinements were proposed, for example the introduction of an optimal multicriteria approach . It should be noted that these iterative methods are still used.

In the nineties, the main progress concerns the fabrication methods with the use of lithographic techniques allowing the fabrication of high precision phase only components etched into quartz.

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Since the availability of SLMs was an important issue for the success of optical information processing, a lot of effort has been invested after 1980 into the development of SLMs fulfilling the optical processors requirements in terms of speed, resolution, and size and modulation capability. A paper written by Fisher and Lee gives the status of the 2D SLM technology in 1987 and shows that, at this time, the best feasible SLM performance values are found to include:

about 100 × 100 resolution elements, 10-Hz framing rates, 1-s storage, less than 50 $\mu$J/cm$^2$ sensitivity, five-level dynamic range, and 10-percent spatial uniformity.

Many different SLMs have been proposed and many prototypes fabricated—for example, besides liquid crystal SLMs, magneto-optic SLMs , multiple quantum wells devices (MQW) , Si PLZT SLMs and Deformable Mirror Devices . However very few of these SLMs have survived. Therefore, today, among the SLMs commercially available, mostly for display purpose, two technologies prevail: liquid crystal technology and Digital Micromirrors Devices DMD (MEMS based technology).

In conclusion, since the origin of the optical processors, commercially available SLMs are fulfilling the requirements in terms of speed, modulation capability, and resolution. The applications of SLMs are numerous, for example, recent papers have reported different applications of LCoS SLMs, such as pulse shaping ,quantum key distribution , hologram reconstruction , computer generated holograms , DOEs , optical tweezers , optical metrology.

## 5. Optical Computing Today

The traditional field of optical computing is no longer so active, it has evolved tremendously. Today, numerous research topics benefit from the results of the research in optical computing and therefore the field is perhaps no longer so well defined. Several signs show that the activity has changed.

The research on optical correlators is continued by fewer research teams, however it should be noted that the Jet Propulsion Laboratory (JPL) is still working on optical correlators for real time automatic target recognition.

Some of the algorithms developed for pattern recognition initially for optical processing are now used success- fully in digital computers. DOEs are now a part of numerous industrial products. All the research on the fabrication of DOEs made possible the fabrication of nano structures and very exciting new fields of research such as nan photonics , nanofluidics and optofluidics .

Biophotonics is an exponentially growing field that is largely benefiting from the past research in optical process- ing. Typical examples are the optical tweezers and the optical trapping.

Thanks to the digital holography, where the holographic plate is replaced by a camera, holography is particularly used for the quality control of manufactured products, and for digital holographic microscopy.

## 6. Conclusions

The history of optical computing reveals an extraordinary scientific adventure. It started with the processing power of coherent light and particularly its Fourier transform capability.

The history shows that considerable efforts were dedicated to the construction of optical processors that could process a large amount of data in considerable amount of time. Today, Optics is very successful in information systems such as communications and memories compared to its relative failure in computing.

All the research results in optical computing contribute strongly to the development of new research topics such as biophotonics, nanophotonics, optofluidics, and femtosecond nonlinear optics. But, the dream of an all optical computer overcoming the digital computer never became reality, and optical correlators for pattern recognition have almost disappeared. The speed of the optical processor was always limited by the speed of the input and output devices. Digital computer have progressed very rapidly, the Moore's law is still valid, multi-core processors are more powerful, and it is clear that digital computer are easier to use and offers more flexibility. Digital computers have progressed faster than optical processors. Optical computing is mostly analogue when electronic computing is digital. Due to the lack of appropriate optical components digital optical computers were not able to compete with the electronic. The solution to this is to associate optics and electronics and to use optics only when it can bring something that electronics cannot do. .

The potential of optics for parallel real time processing remains and the future will tell if optical computing will be back, for example, by using nanotechnologies.

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ISSN 2229-5518