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Optical information processing: A historical overview

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A B S T R A C T

Optical information processing lies at the intersection of optics and signal processing. It involves the processing of optical information as well as the use of optical means to process information, the later being the main emphasis of this work. A historical review of various forms of optical signal processing and holography, optoelectronic and digital optical computing, and optical interconnections is given.

1. Introduction

The electromagnetic spectrum consists of different frequencies of radiation. Those frequencies which the human eye can sense are referred to as light. It is convenient to include frequencies somewhat below (infrared) or somewhat above (ultraviolet) the visible frequencies in this definition. Optics is the study of physical phenomena involving light, including not only visible but also infrared and ultraviolet frequencies. It deals with the behavior of light and its interaction with matter. It also includes the technology built around our attempts to utilize light for various purposes.

Optical information processing is a branch of optics. It can mean two separate things: (i) the processing of optical information; (ii) optical means of processing information. (The two will coincide if we optically process optical information.) Of these two interpretations, the second will be our main interest.

Light is electromagnetic radiation, which in general is a space- and time-dependent vector field. The term optical information means the information carried in this light field. Light coming from a distant stellar object and captured by a telescope carries information about the object to us. Light traveling through a medical endoscope carries information about the condition of a patients organs. We can express this information as functions such as $\mathbf{f}(t)$ or $\mathbf{f}(x)$, or in the most general case $\mathbf{f}(x, y, z, t)$. Here t is time and x, y, z are spatial coordinates. $\mathbf{f}$ may represent the electric of magnetic field. In optics, a scalar treatment is often sufficient, in which case we deal with only one component of the vector field, so we deal with scalar functions $f(x, y, z, t)$. Sometimes, especially with incoherent fields, it is preferable to work with the intensity, rather than the amplitude as a function of space and time. Information may also be carried by the polarization or wavelength.

Images captured by our eyes or a camera are not the only form of optical information. An optical telecommunications fiber will carry optical signals which are functions of time. Spectroscopic methods provide us displays of the emission or absorption at different wavelengths.

We process optical information for many purposes. We may want to eliminate noise, correct distortions, or transform an image in a way that makes it easier to interpret, or simply more appealing. Given the flexibility and power of modern digital computers, most processing of optical information today is accomplished digitally. If we are dealing with optical images, this is called digital image processing. We will not deal with digital processing here. Though rarer, analog optical systems are also used to process optical information, often in specialized situations where speed or throughput justifies the implementation of a custom system.

Another way to contextualize the focus of this paper is to recall the four main areas of information technology: storage, communication, sensing, and processing of information. Optics plays an important role in information storage in the form of optical disks. Likewise, it plays an important role in communications in the form of optical fibers. Consumer product remote controls are examples of wireless optical communication. Optical sensors include both cameras (image sensors), as well as photodetectors (point sensors). The processing of information by optical means is far less established compared to storage, communications, and sensing, but may hold the greatest promise.

Historically, over several decades, optics has replaced electrical/electronic techniques in storage and communications to an increasing degree. There is some reason to believe that optics will also replace electronic techniques of information processing as time progresses. This claim is far from being universally agreed

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upon, but it is nevertheless widely agreed that optical techniques will have a greater role to play in the processing of information. A commonly voiced viewpoint is that optics will be used to complement electronics, rather than replace it. Thus, rather than "optical computing", some prefer the term "optics in computing".

To make it clear what we mean by "optical processing", we should perhaps recall what other forms of processing are available. The information to be processed must first be represented in terms of a physical quantity. A certain number can be represented, for instance, by a voltage on a resistor, the rate of fluid flow through a pipe, the position of a wheel, the amplitude of a sound wave, or the intensity of a light beam. Once represented in a physical manner, information can be transmitted and interact with other pieces of information to achieve some desired result. The distinction between hydraulic, acoustical, mechanical, electronic, or optical processing lies in how we represent the information and through what kind of physical interactions it is processed.

Building optical computers has been a long-time endeavor, supported by a number of good reasons, such as the potential for speed and throughput arising from the high speed and frequency of light, and the relative freedom from various forms of resistance and dissipation that are substantial in many kinds of computing. Unfortunately, various obstacles have limited accomplishments in optical computing to select and special-purpose situations. Building an all-purpose general optical digital computer has remained a moving target, despite success in the areas of storage, communication, and sensing. It remains to be seen whether conditions that favor the huge potential of optical-electronic hybrid computers, or even an all-purpose digital optical computer will be realized as a result of advances in nanotechnology.

This paper will take a historical perspective. However, the sections do not correspond to historical epochs; rather, we will discuss different ways of using optics in each section. Section 2 will deal with analog optical information processing, and the following section will deal with digital optical computing. Section 4 will discuss optical interconnections and optoelectronic computers. Section 5 will discuss the increasing diversity of approaches and try to briefly touch upon some recent trends.

2. Analog optical information processing

2.1. Analog processing

Since most processing systems today are digital, it is worth recalling what analog processing is. For instance, if we represent the number 3 with 3 ml of water in a graduated cylinder and add to it 2 ml of water from another, we may read the result of the operation $2+3$ from the graduated cylinder as 5. This is a consequence of the conservation of matter and the incompressibility of water. Likewise, analog optical information processing involves representation of information with either the amplitude or intensity of light. (In some cases, the polarization or wavelength can also be used.) To optically perform the addition operation, we may use two light sources with adjustable intensity and a device that can measure intensity. We adjust the sources to represent the numbers to be added and direct the light from both towards the measurement instrument, from which we can read the sum of the two numbers.

If the objective is multiplication, one of the numbers can be represented as the amplitude of a light beam. The other number can be represented as the transmittance factor of a partially transparent material such that, if the number is 1 all of the light is transmitted, if the number is 0 none of the light is transmitted (an opaque material), and if the number is 0.5 half the amplitude is transmitted. When the light passes through this material, the result of the multiplication is proportional to the amplitude of the exiting light. This seems to restrict the multiplier between 0 and 1 but this is easily overcome through suitable scaling.

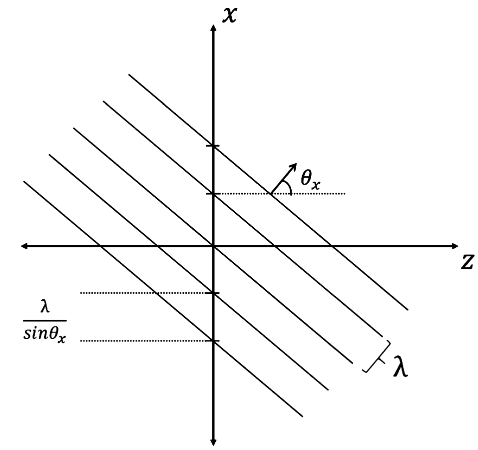

Fig. 1. Plane wave making angle θ_x with the z-axis.

These operations are not limited to a single pair of numbers to be added or multiplied. Large arrays and high-resolution images can be similarly processed. With addition and multiplication in hand, any linear combination can be optically realized. This includes all linear systems and transformations, which can be realized in the time it takes light to pass through the system and be registered by the detectors.

2.2. Fourier optics

Of central importance is the close connection between the propagation of light and frequency-domain concepts. In fact, these connections are so significant, the area of analog optical signal processing is also referred to as "Fourier optics" [1]. With reference to Fig. 1, consider a plane wave with wavelength λ whose propagation vector lies in the x-z plane, making angle θ_x with the z-axis. The parallel lines represent the side-view of the planar wavefronts. The peaks, when viewed along the x-axis, are spaced $\lambda/\sin\theta_x$ apart. Thus the profiles of plane waves making different angles are harmonic functions (complex exponentials, sines, cosines) of different spatial frequency along the x-axis. Now, consider an image $f(x, y)$ in the x-y plane. It can be Fourier analyzed and represented as a sum of complex exponentials with differing frequencies. Each of these different frequencies correspond to plane waves making different angles with respect to the z-axis. Thus, using Fourier analysis to decompose an image into complex exponentials, directly corresponds to decomposing a propagating wave into plane waves making different angles. Just as complex exponentials are eigenfunctions of shift-invariant systems, plane waves are eigenfunctions of propagation through free space. If there is an aperture in the system, plane waves making large angles (corresponding to high frequencies) will be blocked by this aperture. Thus the aperture acts like a low-pass filter. This is the physical basis through which the frequency resolution of optical instruments, such as microscopes and telescopes are determined. These close connections, realized over a century ago by Ernst Abbe working with Carl Zeiss, not only makes linear systems theory and Fourier analysis relevant to the study of optical propagation, it also makes optics a suitable medium in which to realize linear systems and transformations.

In particular, the Fourier transformation can be implemented with striking ease using a single convex lens (left half of Fig. 2). We situate a lens of certain focal length f, a distance f to the right of the original image. Then the Fourier transform is displayed another distance f further right from the lens. Being able to real-

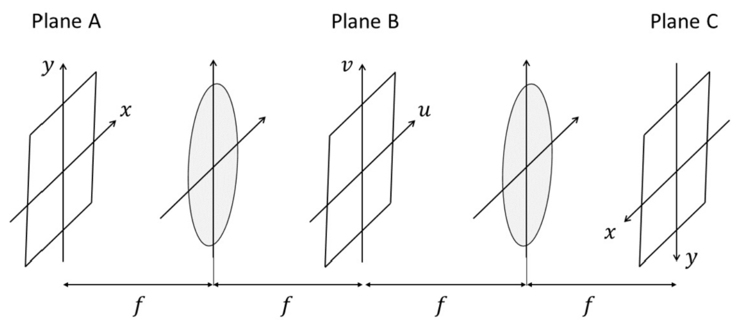

Fig. 2. The two-dimensional Fourier transform of the image on the plane A is observed on the plane B as a result of propagating through free space and passage through a convex lens. At plane B, the image is multiplied with a partially transparent mask to impart the desired frequency response. Then an inverse two-dimensional Fourier transform is performed (which is the same as a forward transform with inverted axes) to transform back to the original domain at plane C. f is the focal length of the convex lenses.

ize the Fourier transform, combined with the ability of multiplying an image with a partially transparent mask means that frequency-domain filtering can be achieved with ease. (Notice that in the case of ideal filters, the filter can be realized simply by cutting holes in a piece of opaque material, with no issue of realizability as is the case with causal temporal systems; thus perfect lowpass filters can be readily achieved.) Large resolution images or arrays can be convolved with desired impulse responses, or filtered with desired frequency responses, in the time it takes light to pass from one end of the system to another. This has applications in image recovery, restoration, pattern recognition, and so forth.

While highly attractive, we must not forget that this is an analog system. Therefore, if many repeated operations are performed, there will be an accumulation of noise that ultimately makes the result unreliable. Therefore, the number of steps to be performed must not be large. One way such systems can be useful is as an initial high-speed pre-processing stage of a system that will subsequently involve analog-digital conversion and digital processing.

The mathematics of the concepts outlined here may be found in texts such as [2–8]. These fundamentals have been known for a long time. Elementary operations based on the above-mentioned Fourier concepts have been experimented with in the fifties, but progress was hindered by the absence of *coherent* light sources. During the sixties, lasers became available and satisfied the need for high-quality light sources. This was accompanied by increasing application of signal and communications theory concepts from electrical engineering to the study of optical systems. Optics was no longer of interest only to physicists.

2.3. Applications and architectures

The above mentioned developments led to rapid progress and led to the golden age of analog optical signal processing. A historical account of the period up to around 1990 may be found in [9,10]. A crucial factor that enabled this development was the relatively less-developed state of digital computing during the sixties and seventies. This legitimized optical processing systems that could provide very high-speed processing of large arrays and images that was unthinkable with digital computers of the time. (To foreshadow later developments, we may note that while analog optical processing systems still offer very fast processing of large arrays and images, today digital computers have come to a point where the advantage of flexibility and the prevention of noise and error accumulation, often outweigh the advantages of optical processing with some exceptions.)

The sixties witnessed the development of complex systems of increasing complexity. They were used to address problems that digital computers of the time were incapable of dealing with. One example was the processing of the huge amounts of synthetic-

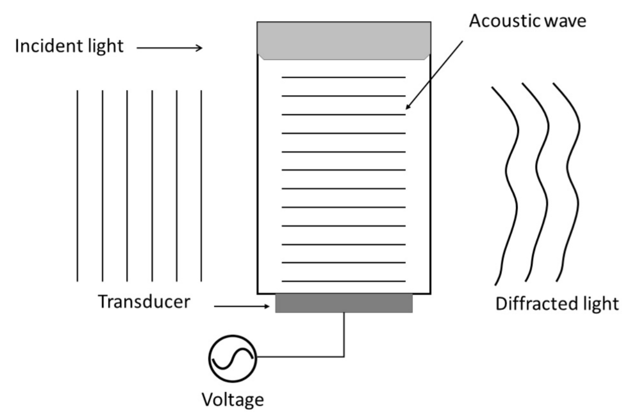

Fig. 3. Acousto-optical signal processor. The high-bandwidth electrical signal is applied at the bottom to a transducer which launches it as an acoustical wave. This alters the optical properties and thus modulates the light coming from the left. The overall effect is to change an electrical temporal signal to a optical spatial signal which can then be processed like an image, perhaps by using the system shown in Figure 2.

aperture radar (SAR) data [11], for which some of the most complex optical processing systems were devised. [9]

A very innovative approach to processing mostly one-dimensional high-bandwidth signals was based on acousto-optical devices. These were used to convert electrical signals to optical signals. The electrical signal to be processed was transduced into an acoustic wave and launched transversally into a material through which it propagated acoustically. The pressure wave through the material created changes in the material that ultimately locally altered its optical characteristics and thus modulated the light passing through it. This was a means of converting high-bandwidth electrical temporal signals to optical spatial signals, which could then be processed with the means already outlined (Fig. 3). A recent special issue on acousto-optics is [12].

Another remarkably inventive idea witnessed in the sixties was the use of holographic approaches to realize desired complex frequency responses, not just ideal filters. They were utilized especially for pattern recognition applications based on complex matched filters. One notable scheme we will not be able to discuss in detail was the VanderLugt correlator [13]. A few notable and representative works might include [14,15]. Two compilations on optical pattern recognition are [16,17].

Moving into the seventies, approaches of the earlier decade were extended and further developed. Among the totally new developments we might mention matrix processing systems [18,19]. An important legacy of these was the example they set for digital computing architectures that would be proposed later (based on their treating spatial coordinates as discrete variables). A typical

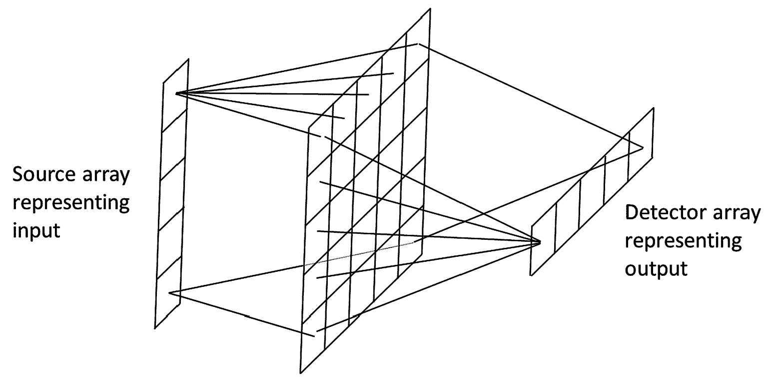

Fig. 4. Matrix-vector product architecture.

matrix-vector product architecture is shown in Fig. 4. The source array on the left launches a vector, with each source representing one element of the vector. The emanating light is spread in the horizontal direction so that the light coming out of each source falls on all elements of a separate row of the matrix. As the light passes through the matrix, which consists of a partially transparent material, it is multiplied by the coefficients. Then, the emanating light is collected vertically onto a detector array, the collected light being effectively summed as a result of linear superposition. The overall operation precisely corresponds to matrix-vector multiplication. Again, the advantage is that very large arrays can be processed in the time it takes light to travel from one end of the system to the other, and the disadvantage lies with the analog nature of the operation.

Another area that received increasing attention from the seventies onward was the development of algorithms for the retrieval of phase information from intensity measurements. Traditionally, optical measurement instruments can only measure optical intensity, and not phase, and utilizing multiple measurements or additional a priori information to recover the phase has remained a challenging problem that has often been addressed by iterative methods. This falls under a broader set of problems known as image recovery and reconstruction, which has received substantial attention during the seventies and beyond. [20,21]. A relatively recent approach is referred to as Fourier ptychography, where multiple-plane-wave illumination is used with different angles to achieve a high-resolution and wide-field image [22,23]. An example of a speckle-based approach to high-resolution imaging is [24].

Again during this period, the concept of hybrid optical signal processing was developed. This involved the use of optical systems in conjunction with electronics, or with digital computers to combine the benefits of both. The optical part would bring fast processing of large arrays, high-resolution images, or high-bandwidth data, and the digital part would bring flexibility and control of error accumulation. Such systems might involve iterative or feedback loops. Examples of such systems may be found in [25,26]. A compilation that gives a good idea of the state-of-the-art of optical signal processing in the mid eighties is [27].

Before we continue, we briefly talk about holography, which has always been an integral branch of analog optical information processing. In popular culture, the term holography is almost synonymous with three-dimensional imaging, but more precisely it is the act of capturing and recording the whole information in a propagating wave, such that it can later be re-launched ("played back") and continue to propagate. Ordinarily, if we capture an image using conventional photography, be it chemical or digital, only the intensity and thus amplitude information is recorded and the phase information is lost. Thus, we do not have all the information necessary to reconstruct the wave. Objects are perceived as a result of light waves bouncing off from them and finding their way to our eyes. Holography allows not only the amplitude but also the phase to be captured so that complete information of the propagating light is preserved. This is based on the principle of adding the complex field to a constant reference before intensity recording [3,13]. When the field is reconstructed, it is (ideally) the very same light wave that was coming to us from the original object so that out perception is also the same as with the original object, including depth cues, which is what allows the sense of three-dimensional perception. Beyond recording of three-dimensional information, holography has important applications in optically realizing systems with complex transfer functions, metrology, high-density information storage and the routing of light beams in complex patterns. Three-dimensional television, a long-time objective of holography, may be a reality within the foreseeable future. Computer-generated holography has been an alternative means of creating holograms for a long time [28]. Today, digital holography is a well-developed area with close connections to three-dimensional imaging [29,30].

In some ways, the eighties could be viewed as a time of relative stagnation for analog optical information processing. The lack of large-scale commercial applications was disappointing, despite the success of certain specialized applications. Another reason why the level of novel activity was relatively low was because many researchers working in this area turned their attention to optical interconnections and digital optical computing, which we will discuss in section 3.

2.4. Space-frequency approaches and fractional Fourier and linear canonical transforms

An important body of work was that relating Fourier optics concepts to the space-frequency plane or phase space. These extended the classical formulation of Fourier optics to space-frequency distributions such as the Wigner distribution and ambiguity function [31–33]. Coinciding with strong interest in time-frequency representations in signal processing, this work solidified and provided mathematical precision to the concepts of the space-bandwidth product and the number of degrees of freedom of an optical signal that had already been in currency since the sixties [34,35]. These essentially refer to how many numbers are required to uniquely specify a signal and are closely related to the physics of wave propagation and the characteristics of optical components, as well as sampling theory. Recent work extending these ideas include [36–38].

Analog optical information processing saw a substantial revival in the early nineties following the introduction of the fractional Fourier transform (FRT) to the area [39–43]. In fact, in a study of the whole field of optics and photonics made by the ISI covering nearly 70,000 papers published over the nineties in nearly 50 journals, the theory, application and implementation of fractional

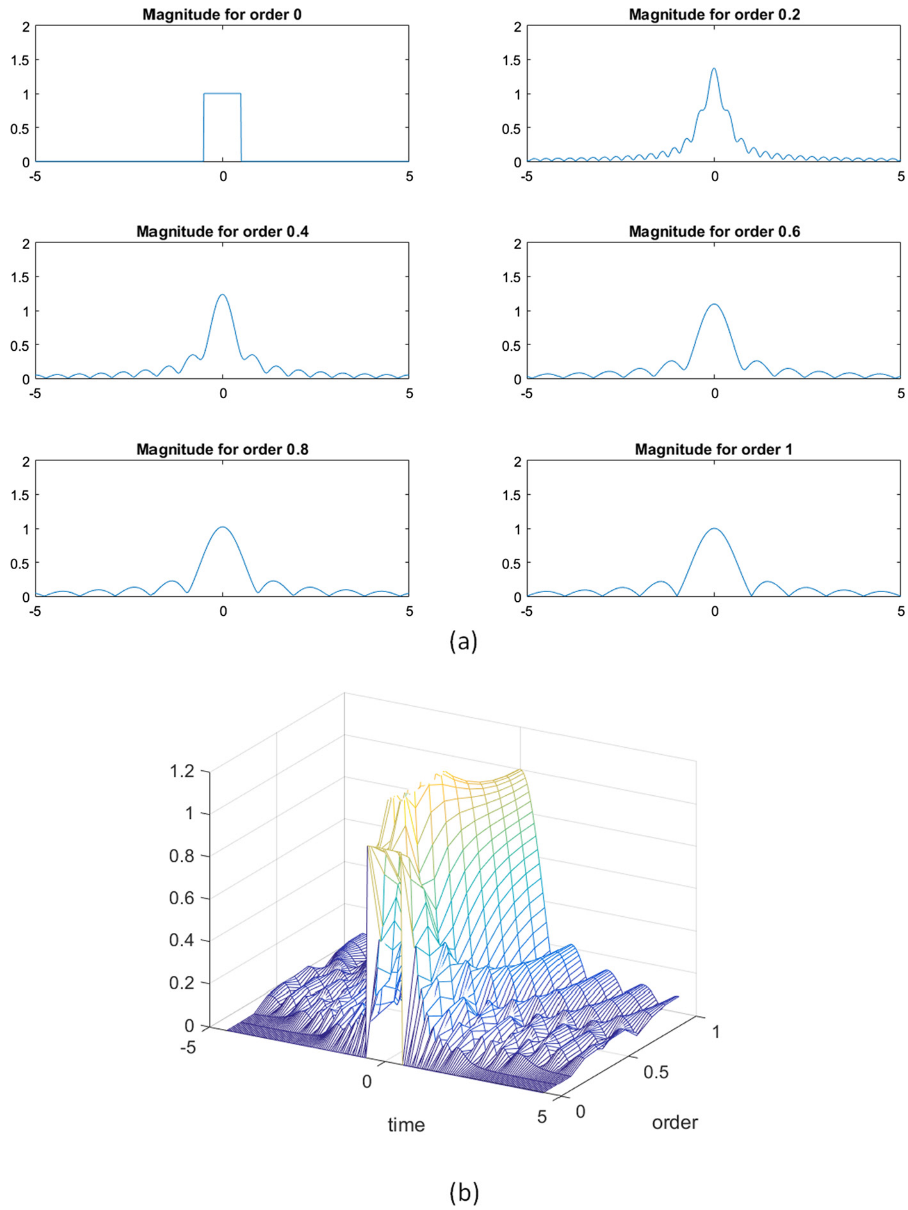

Fig. 5. Magnitude of the fractional Fourier transform of the rectangle function (a) for the orders $a = 0, 0.2, 0.4, 0.6, 0.8, 1$, (b) for orders a in the interval $[0, 1]$.

Fourier transforms in optics, was noted as the second leading research theme in the field by the ISI [44]. Interest in the FRT later evolved to an interest in linear canonical transforms, which continues to this day.

The fractional Fourier transform (FRT) is defined by generalizing the conventional Fourier transform by introducing an order parameter a. When $a = 0$, we have a zeroth-order transform of the function, which is the original function. When $a = 1$, we have a first-order transform, which is simply the conventional Fourier transform of the function. If we take $a = 1/3$, we have an operation, if repeated three times, that gives us the conventional Fourier transform. The 0.4th transform of the 0.3rd transform is the 0.7th Fourier transform. If we have negative orders, these correspond to inverse transforms. The transform with order $-a$ is the inverse transform of the transform with order a. In particular, when $a = -1$ we have the inverse conventional Fourier transform.

Fig. 5 shows the magnitude of the various ordered fractional Fourier transforms of the rectangle function. We can clearly see how it evolves into a sinc function as the order a changes from 0 to 1.

The ath fractional Fourier transform $f_a(u_a)$ of a function $f(u)$ can be defined in multiple ways, the simplest being as a linear integral transform:

$$f_a(u_a) = \int_{-\infty}^{\infty} K_a(u_a, u) f(u)\, du, \quad (1)$$

$$K_a(u_a, u) = A_\alpha \exp\left[i\pi\left(\cot\alpha\, u_a^2 - 2\csc\alpha\, u_a u + \cot\alpha\, u^2\right)\right],$$

where $A_\alpha = \sqrt{1 - i\cot\alpha}$ and $\alpha = \frac{a\pi}{2}$. When $a \neq 2j$ and $K_a(u_a, u) = \delta(u_a - u)$ when $a = 4j$ and $K_a(u_a, u) = \delta(u_a + u)$ when $a = 4j \pm 2$, where j is an integer. Here u_a denotes the coordinate variable in the ath order fractional Fourier transform, as we will discuss below.

Just as conventional Fourier transformation corresponds to a $\pi/2$ rotation in the time-frequency (or space-frequency) plane, fractional Fourier transformation of order a corresponds to a $a\pi/2$ rotation (Fig. 6). In fact, this is one of the alternative ways of defining the FRT. For instance, the Wigner distribution of the FRT of a

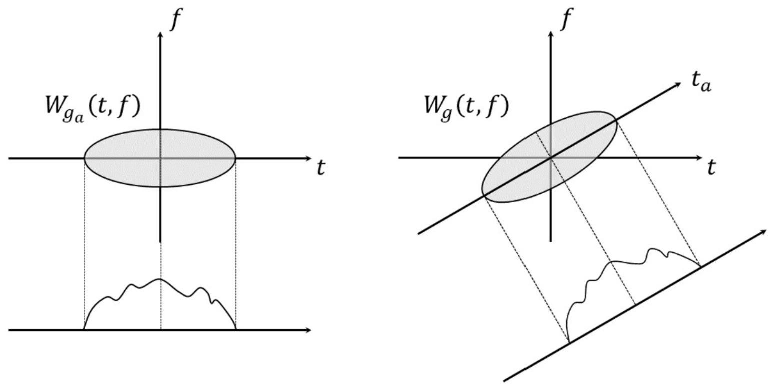

Fig. 6. Rotation in the space-frequency plane. The Wigner distribution $W_{g_a}(t, f)$ of the FRT g_a of a function g (left) is a rotated version of the Wigner distribution of the original function g (right). The projections of the Wigner distribution onto any fractional Fourier domain give the squared magnitude of the representation of the function in that domain.

function is a $a\pi/2$ rotated version of the Wigner distribution of the original [2,42,45].

Just as we can enact the operation of convolving with an impulse response by first taking the Fourier transform of a signal, multiplying it with the frequency response, and then inverse transforming back to the original domain, we can also undertake filtering in fractional Fourier domains by taking the ath order fractional transform, applying a filter in the ath order fractional Fourier domain, and then inverse transforming to the original domain. This has led to concepts such as fractional convolution and fractional Fourier domain filtering. It has been shown that optimal filtering in fractional Fourier domains can result in reduced mean-square errors in the presence of time-varying distortions and/or non-stationary noise [46–48]. Likewise, correlation and matched filtering operations used for pattern recognition applications have been generalized with the FRT [49].

The concept of filtering in fractional Fourier domains can be further generalized to multistage and multichannel filtering, as illustrated in Fig. 7. Going one step further, we can obtain generalized filtering circuits as in Fig. 8. These configurations provide substantial generalizations of ordinary shift-invariant systems [50].

The ath order fractional Fourier domain is where the ath order fractional Fourier transform of a function lives. It makes angle $a\pi/2$ with the time (or space) coordinate axis in the time- (or space-) frequency plane, in accordance with the rotation theorem mentioned above [51].

An important result relating the FRT to optics is that the propagation of light, as well as other waves satisfying similar wave equations, is a process of continual fractional Fourier transformation. Consider a transverse distribution of light at a certain plane parallel to the x-y plane, that propagates along the z-axis towards the right. The original light distribution is the 0th FRT. Slightly to the right, we will observe the ath order FRT for a small value of a. As we move along the z-axis to increasing values of z, the order a will increase such that as z goes to infinity, a will approach 1 according to an inverse tangent function, corresponding to the well-known result that the far-field diffraction pattern is the Fourier transform. [2,52–54]

This propagation result can be generalized to more general systems including arbitrary concatenations of thin lenses separated by arbitrary distances. The original function corresponds to the 0th fractional Fourier transform, presented at the input on the left. As we move towards the right, the fractional order will increase and the light distribution will undergo fractional transforms with monotonically increasing fractional orders [2,52].

It is possible to realize the fractional Fourier transform by using a convex lens, in a manner similar to the realization of the conventional Fourier transform. Thus, optical signal processing systems based on the conventional Fourier transform can be easily generalized to fractional Fourier transforms, without any increase in hardware complexity or cost. In particular, optimal filtering in fractional Fourier domains and fractional convolution can be realized optically. This is achieved by nothing more difficult than adjusting the distances between the lenses in Fig. 2 [2,52].

We also note that the fractional Fourier transform can be computed in the order of $N \log N$ time, so that performance improvements come without any additional computational cost [55]. Recent reviews on the fractional Fourier transform include [56,57].

The fractional Fourier transform can be further generalized to the linear canonical transform (LCT), which has three parameters. LCTs can also be defined as linear integral transforms [2,58]:

$$f_{\mathbf{M}}(u') = \int_{-\infty}^{\infty} C_{\mathbf{M}}(u', u) f(u)\, du, \tag{2}$$

$$C_{\mathbf{M}}(u', u) = A_{\mathbf{M}} \exp\left[i\pi(\alpha u'^2 - 2\beta u' u + \gamma u^2)\right],$$

where $A_{\mathbf{M}} = \sqrt{\beta}\, e^{-i\pi/4}$. α, β, and γ are real parameters independent of u' and u.

Just as the FRT corresponds to rotation in the time- (or space-) frequency plane, the LCT corresponds to a parallelogram distortion, meaning that parallelogram regions are mapped to other parallelogram regions, and other shapes are mapped accordingly. Depending on its three parameters, the family of LCTs includes chirp multiplication, chirp convolution, scaling, fractional and conventional Fourier transformation among its special cases. The concept of filtering in FRT domains has also been extended to filtering in LCT domains, adding further flexibility and potential performance improvements.

Just like the FRT, the LCT can also be optically implemented with relative ease [59] and also can be computed in the order of $N \log N$ time [60], so that once again performance improvements with the LCT come without any additional computational cost.

2.5. Temporal processing

Most work in analog optical information processing deals with spatial signals although similar concepts are also relevant for ultrafast processing of temporal signals; for instance [61]. Many applications require control of optical waves in space and time, a problem referred to as "wavefront shaping". [62] summarizes developments in this area where spatial, temporal and frequency degrees of freedom are used to control the propagation of light. Examples of work on engineering spatially complex light patterns with arbitrary statistical properties are [63,64].

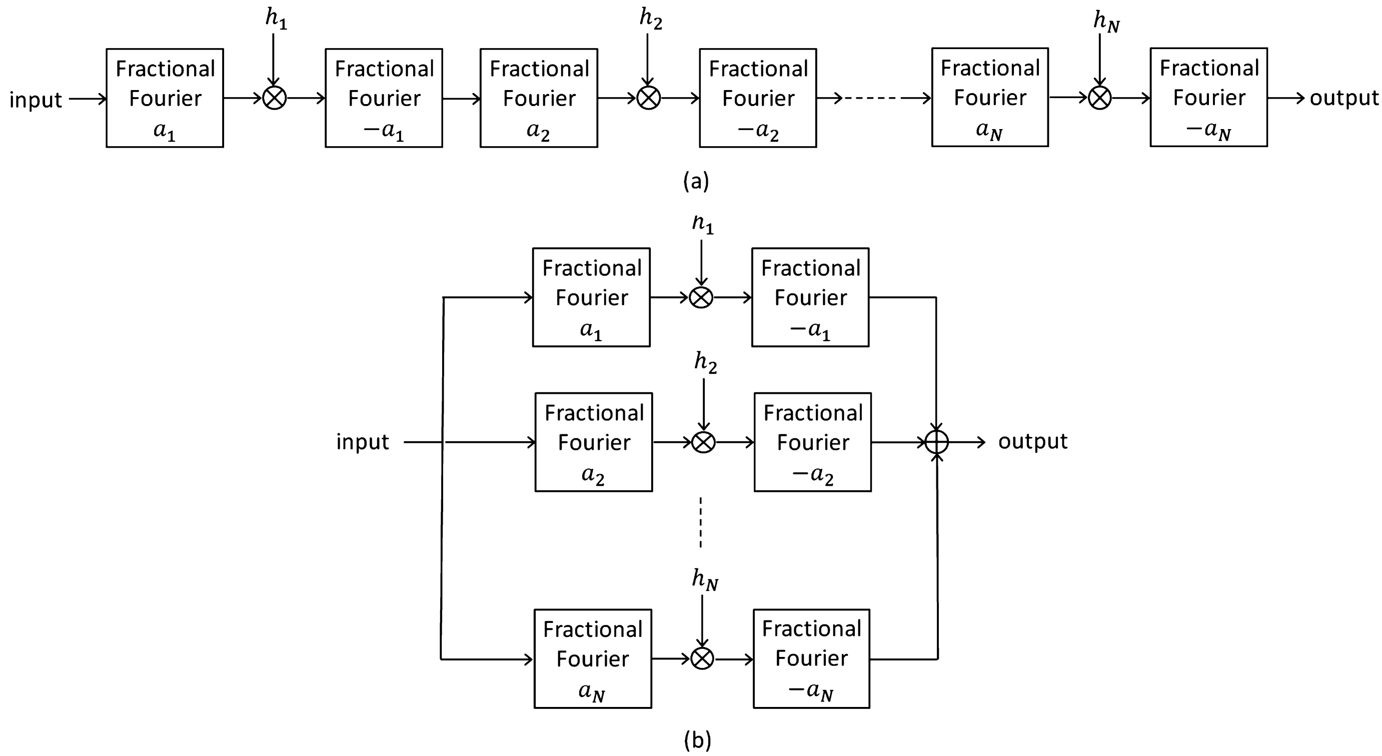

Fig. 7. Multistage (part a) and multichannel (part b) filtering in fractional Fourier domains. The basic building block is an ath order FRT followed by a FRT-domain filter followed by an $-a$th order (inverse) FRT. In part a, this building block is repeated in series with different orders. In part b, it is repeated in parallel.

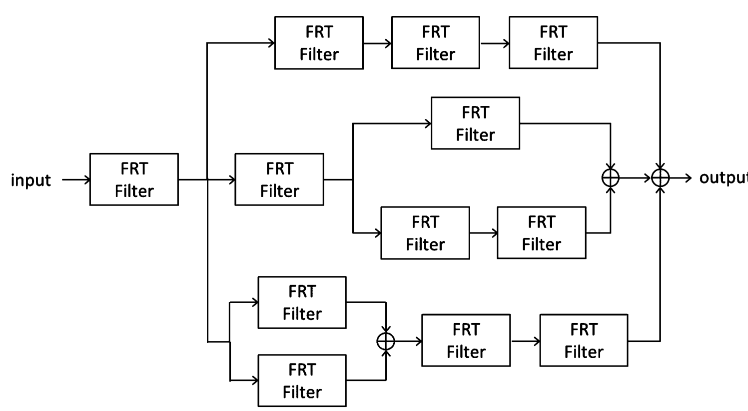

Fig. 8. Generalized filtering configurations in fractional Fourier domains. The basic building block in Figure 7 is repeated in arbitrary series and parallel configurations.

3. Digital optical computing

3.1. Digital optical devices

Today, a computer essentially means a digital computer. The concept of an optical digital computer is far from new. What is the defining characteristic of an optical computer versus an electronic one? In earlier times, this was considered to be its use of optical switches, transistors or gates, instead of electronic ones. There are many ways of building nonlinear optical devices that can serve as transistors or gates. It would be fair to say that a very substantial effort has gone into the development of novel ideas, physical mechanisms, and means of manufacturing large arrays of such devices. Unlike electronic transistors or gates that operate with voltages or currents, optical transistors or gates work with light beams. The existence of light can represent a logic 1 and its nonexistence a logic 0. Logic operations rely on the principles of interaction of light and matter.

3.2. Approaches and architectures

It was quickly realized that merely replacing electronic transistors with optical ones was not a smart way to create optical computers. Traditional computer architecture evolved in a manner to benefit from the strengths of electronics and circumvent its weaknesses. The Von Neumann architecture is a primary example of this [65,66]. However, neither the strengths nor the weaknesses of optical switches or transistors are similar to that of electronic switches or transistors, so that one would not expect the same type of architecture to be an efficient means of creating optical computers.

As a consequence of this realization, many researchers have proposed a wide variety of architectures for optical computing [67,68]. Some proposed architectures are still based on Boolean logic, in the way most digital electronic computers are. Even then, alternatives have been proposed to the use of switches to construct gates. One creative example is optical logic by shadow casting [69],

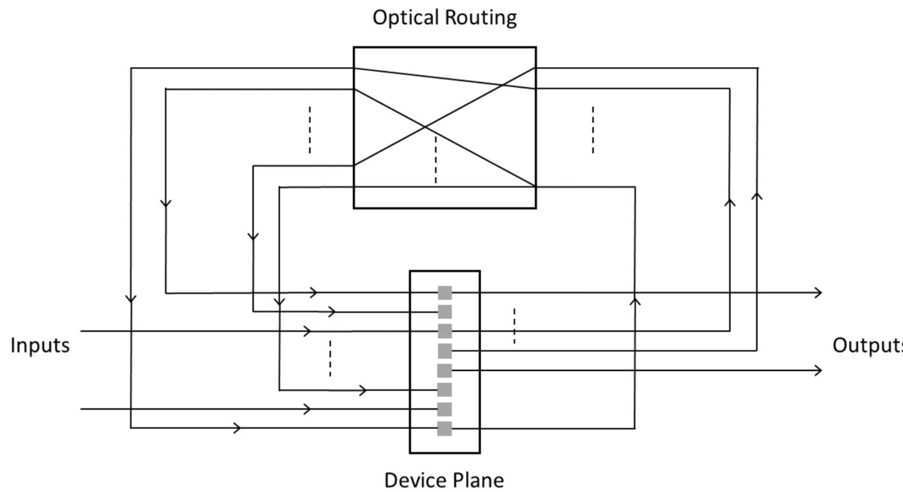

Fig. 9. Optical computer architecture based on an array of optical or optoelectronic switches whose outputs (right of plane) are routed to its inputs (left of plane) with an optical system. This type of system has the general nature of a finite state machine.

where light and dark patterns and semi-transparent masks are used to realize Boolean logic functions. Other innovative alternatives based on different mathematical systems, such as algebraic operations or the substitution of symbols according to predetermined rules are only a few further examples [70].

Integrated optics usually refers to creating planar optical circuits on a substrate, in a manner analogous to integrated electronics. Light signals travel along waveguides and interact either with electrical signals through electro-optic devices, or with other light signals through nonlinear optical interactions. It must be noted that traditionally waveguides cannot be much smaller than the wavelength of light, which limits miniaturization of integrated optical circuits. Nevertheless, with the recent advance of silicon photonics [71], such systems are finding application in a wide variety of communications, sensing, and medical applications, to name a few.

However, why restrict optical circuits to be two-dimensional? One option could be to "wire" discrete optical devices with optical fibers, which is possible, but not being an integrated approach, bulky. This possibility aside, the most promising approach seems to be to use what is referred to as "free-space optics", meaning light travels freely in space to carry signals between the transistors or logic gates [72,73]. In a typical architecture, the transistors, gates, or switches are manufactured in the form of a regular array (Fig. 9). These arrays of devices are manufactured using techniques similar to already mature integrated circuit manufacturing techniques. The devices on these arrays have optical inputs and optical outputs. Typically the inputs are on one side and the outputs are on the other side, although they can both be on the same side as well. Light beams representing logic 1 and logic 0 fall on them, are operated on, and emanate from them. The light beams emanating from the outputs are then optically routed to their desired destination on another such optoelectronic device plane or to the input side of the same array using prisms, mirrors, micro lenses, holographic diffractive elements, etc. The main circuitry consists not of solid wires, but of optical signal paths where light travels through free space. An obvious advantage is that light beams can pass through each other, unlike electrical wires that would short circuit if they touched. Additionally, there is no restriction to two-dimensional topologies. Complex, three-dimensional circuits can be realized. Thus, these architectures are especially suitable for the realization of parallel algorithms.

3.3. *Future prospects*

Along with the above mentioned advantages come certain disadvantages. Optical switches, transistors, logic gates, or other nonlinear devices, generally speaking, tend to have high energy consumption. Linear operations will not require these and can be efficiently implemented, such as the computation of linear transformations. However, more general systems will require nonlinear operations. The following argument has been set forth as the reason for this higher energy consumption. Photons are boson and electrons are fermions. Electrons have strong interactions between them, allowing nonlinear switching operations to be more readily realized. Photons, on the other hand, can only interact through a material medium, and those interactions usually require a certain level of energy to be involved. It is important to note that the very same bosonic and fermionic qualities make photons better for communicating information than electrons, as independent light signals do not interfere with each other in the way that electrical ones do. Thus, this argument has been used to build the thesis that "Photons are better for communication but bad for nonlinear switching operations, and electrons are better for switching operations but bad for communication." While this argument has been extremely catchy and does involve a considerable element of truth, in itself it should not be viewed as ultimate grounds for making decisions in favor of certain approaches over others.

One of the most popular arguments against purely optical computing has its roots more than forty years ago. Since optical switches consume high amounts of power, there would be a large amount of heat that would be generated and that would have to be removed. Influenced by these arguments, many researchers, from the eighties onward, started concentrating on the use of optics for communication inside computers, which was referred to as optical interconnections, and frowned upon the prospect of all optical computers. It is most likely that to the extent that optics will have a role to play in computing systems, in the near term, this is more likely to be in the form of optical interconnections, rather than optical switching.

It is our opinion that digital optical computing remains a viable alternative, at least in principle. First of all, much lower energy consuming optical devices are becoming possible (although still not as low as purely electronic switching). But more importantly, since the eighties it is now realized that most of the energy dissipated in a computer comes from the interconnections, not the switches. This totally turns the table. Optical switches

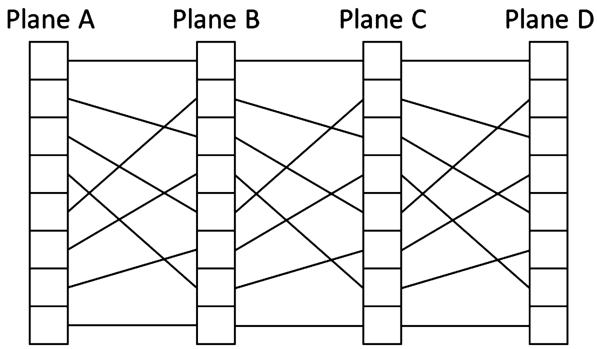

Fig. 10. Multistage interconnection network. Each plane consists of a large array of optical or optoelectronic switches. The arrays are connected to each other through free-space optical interconnections according to a regular interconnection pattern. The number of stages is typically proportional to the logarithm of the number of channels to be switched. With this number of stages, it is possible to achieve desired permutations of connections between the leftmost and rightmost planes.

still consume more energy than electronic switches. However, optical interconnections, especially longer distance ones, consume less energy than electrical interconnections. With switching consuming only a fraction of the energy of a computing system overall, whether to use optics or electronics for switching will not be dictated by energy considerations but by other considerations, which may favor optics.

What is an optical switch? As noted, photons interact with photons through the mediation of matter and often electronic effects. Thus, we can understand an optical switch, effectively, as the combination of a light detecting device, an electrical switch, and a light emitting device. So, if all the interconnections are made optical, but the switches remain electronic, it seems that there is no sense not to replace the detector-switch-emitter combinations by optical switches as well.

Laboratory demonstrations of optical computers have been created during the early nineties. Contemporaneously, optical communications switches were also demonstrated. Since high-throughput communications systems employ fiber optical cables, which are often bottlenecked by electronic switching stages and cannot achieve their potential, it is very attractive to use optical switching for this purpose (Fig. 10) [74,75]. Such systems may be viewed as specialized optical computers and the technology developed for them may pave the way for general-purpose optical digital computers. Optical architectures for several common networks have been devised [76,77].

Despite considerable activity for many decades, the promise of optical computing has not yet been fulfilled. Our opinion about the reasons are as follows. First of all, the reason is not fundamental. It is not because of basic properties of photons or electrons. A case can be made against mechanical or hydraulic computing in that these systems simply cannot deliver the same computational efficiency when compared to electronics on an energy basis (although nano-scale versions may change this conclusion). This is far from being so clearly established in the case of optics. There are two reasons which have actually contributed, in our opinion [78]. The first is that the information processing and computing industry is very heavily invested in the current technology of designing and manufacturing electronics computers. This is not just about the huge cost of lithography machines and other equipment. Decades of research has solved countless problems and overcome an infinitude of obstacles that would otherwise have prevented the systems we have today from becoming reality. Had the same effort went into optical computers, they might also have been a reality. However at this point, it is not easy for sufficient incentive to build up to justify such massive research and risk-taking. This will only be the case if it becomes clear that the use of optics will offer huge advantages that make it worth the undertaking.

Another reason is that, at this point, no one really knows the best way to make an optical or optoelectronic computer. As we already discussed earlier, optics and electronics have different strengths and weaknesses. Thus, traditional computer architecture on which the vast majority of modern systems are based on will clearly not be a viable, let alone optimal, path to follow. Moreover, it does not end with architecture. It is also about algorithms and the methodology with which we build computers, which are inseparable. For instance, consider the architecture shown in Fig. 9, which can be used to implement a finite state machine, which can, in principal form the basis of a general-purpose computer. However, modern computers are based upon a co-hierarchy of hardware and software that has co-evolved along a particular historical path, as a consequence of momentous effort and investment [78–80]. It is not realistic to expect anything on a par with that to emerge easily. The truth is, although there are many ideas, today no one really knows the best way to come up with an integrated architectural and algorithmic structure that would unleash the potential of optical computing. Is there a way out of this deadlock? Perhaps. Stepping stones in the form of special-purpose processors, such as numerical processors, matrix processors, logic arrays, switching networks, with relatively simple structure and algorithmic complexity may pave the way for future progress.

Reviews and books on various aspects of optical computing include [81–92].

4. Optical interconnections and optoelectronic computers

4.1. The increasing importance of interconnections

As we swipe a screen, interacting with images and icons, it is easy to forget the physical basis of computing. Numerical or symbolic entities are represented as physical quantities. Then, we use certain physical effects to operate on them. The entities to be operated on must either come to the same place, or somehow make their state visible. Consider comparing two numbers, which is a simple operation that can be performed locally by bringing the two numbers next to each other. The result will also appear in the same locality. However, if the result is going to be compared with some other piece of information, either it must be transmitted somewhere else or the other piece of information must be transmitted here. Since things take up space, everything cannot be in the same locality and must be spread out. Thus, to solve large and complex problems, not only is it necessary to perform many operations, it is also necessary to combine partial results with others, and this requires constant transmission of information around. Thus the important thing is not only how we represent and operate on information, but how information is percolated around a system. [93]

Prior to the eighties, fundamental consideration of the limits of computing systems was mostly based on the speed and energy consumption of the switches. The wires or cables connecting them, much as in an elementary circuit, were idealized and mostly not attached much importance to. However, as computing systems became increasingly complex, communication inside computing systems became much more important. The interconnections started to become the main source of delay, the main consumer of space, and the main generator of power dissipation. There is a simple reason for this. If λ is the minimum feature size, the volume of a switch is $\sim\lambda^3$ while the volume of an interconnection is $\sim\lambda^2 L$, with L being the length of the interconnection. As feature sizes shrink but circuit complexities increase, L does not fall as fast as λ does and might even increase. Thus the space occupied by the interconnections will claim a larger share of the total space occupied by the circuit. Similar arguments can be made for delay and power dissipation. Several geometrical and scaling arguments also indicate that electrical resistance, resistive-capacitive time constants and other factors scale unfavorably as we go to more complex systems. For instance, for a rise-time limited resistive-capacitive interconnection, ideal scaling does not change the time constant if the length is also scaled down with the minimum feature size. However, with more complex systems the length does not scale down so fast, so that the time constants increase.

4.2. Comparison of optical and electrical interconnections

Recall the comparison of photons (which are bosons), and electrons (which are fermions) in the previous section. We noted that electrons can have stronger interactions, a fact consistent with the lower energy dissipated by electronic nonlinear devices. Electronic devices can also be smaller than optical devices since typically optical devices cannot be smaller than the optical wavelength. However, the same qualities of electrons result in resistance and capacitance effects that result in loss of speed and increased size and power consumption for longer interconnections. Why are there no resistive effects associated with optical interconnections? Since optical frequencies are quite high, confinement of optical radiation does not require the use of conductors, as is necessary at lower frequencies. (Optical waves will still be attenuated in insulators as they propagate, but this is usually much less of a concern.) Thus, while electrical interconnections can be faster, smaller, and less energy consuming for shorter connections, they often are slower, and consume more space and energy for longer connections. Generally speaking, optical connections win over in all of these respects for longer connections. Combined with the possibility of truly three-dimensional circuit structures, this can translate into significantly smaller and faster systems. This has led to the concept of making shorter connections electrical and longer connections optical. Thus it has been asked beyond what length of wire or stage of interconnection hierarchy should optical interconnections be preferred over optical ones? [94] Should interconnections at the gate level be made optically, or should optical interconnections be used only between chips, or only between larger units. The threshold distance calculated varies greatly depending on the models used, but some authors have suggested as small as centimeters or even millimeters [94,95].

The concluding sentence of the preceding paragraph is also consistent with the fact that, as time progresses, optical communication has been used over shorter and shorter distances. Long-distance telecommunication has long since heavily relied on optical fibers. Following this, campus networks and local area networks also often rely on optical fibers. Penetration of optical communication to lower levels has been slower, such as connections within buildings, or connecting backplanes and boards. Connecting computer chips, or even gates within chips would be the next step.

Electrical interconnects are also problematic in terms of routing since they must not touch each other, and they exhibit crosstalk and matching problems. Optical interconnections allow three-dimensional circuits to be routed. (Superconducting wires, another important alternative to conventional electrical interconnections, eliminate some, but not all of the negatives of electrical interconnections. They eliminate problems associated with resistance, but do not offer the ability to route three-dimensional circuits in the way optical interconnections can.) As a consequence of these arguments, several researchers have suggested the idea of an optically interconnected electronic computer. The nonlinear operations would be realized by electronic switches (transistors, gates). The interconnections would be optical. It has been argued that such a conception allows the best of both worlds, giving them the opportunity to complement each others strengths and weaknesses.

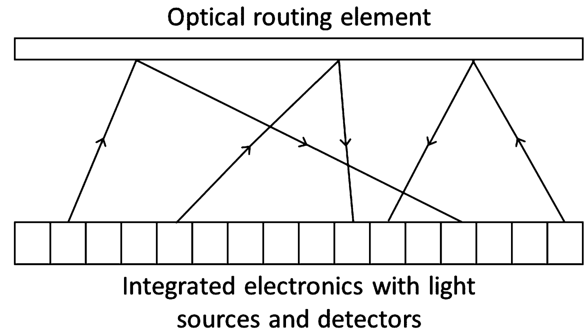

Fig. 11. Optically interconnected electronic computers. The integrated electronic circuits at the bottom have optical sources and detectors that can send and receive information. The optical elements above them can route the light in a manner that will realize the desired circuits.

As alluded to earlier, it is possible to bend some of these arguments in support of all optical computing: If it is the interconnections and not the gates or switches that dominate measures such as space, delay, dissipation, and we have already made the interconnections optical, why not make the gates or switches optical we well (since their contribution to space, delay and dissipation is small anyway)? We must note, however, that this perspective is not broadly accepted.

4.3. Alternatives and architectures

We can provide a few examples of how to employ optical interconnections in digital computing systems. Fig. 11 [96] shows an integrated electronic system which may be a single chip or several side-by-side chips. Normally, interconnections between chips are provided through a printed circuit board. These interconnections are often much more costly in terms of space, delay, and power compared to interconnections within a chip. If optical emitters and detectors are situated on or next to the chips, the light from the emitters can be routed to a detector near the desired destination using mirrors, prisms, micro lenses, holographic elements and so forth. A much larger number of connections can be realized than with a printed circuit board, with greater speed and lower energy consumption.

An alternative approach to providing optical interconnections is the so-called planar optics approach, illustrated in Fig. 12 [97]. Here both the emitters, detectors and optical elements are on the top plane and light is reflected off the bottom surface of an optically transparent material. It is called a folded optical system since the optical elements are designed in a manner that corresponds to a regular optical system where they would have been aligned along the optical axis. However, here the optical axis is folded in such a manner that all of the optical elements lie in the same plane. (It is worth noting that such a system can also be used for analog processing, for instance the system in Fig. 2 can also be folded this way.)

Some recent developments in the area include graphene based optical interconnects [98], carbon nanotube based interconnections [99], unified inter- and intra-chip optical networks [100], micro-electromechanical systems (MEMS) based interconnects [101]. Reviews of optical interconnections in computing include [102–106].

5. Recent developments and the legacy of optical information processing as a view to the future

While traditional analog optical information processing as a self-contained field (often referred to as Fourier optics), has reached a certain level of maturity, the field has evolved and merged into other disciplines and its legacy continues to be felt

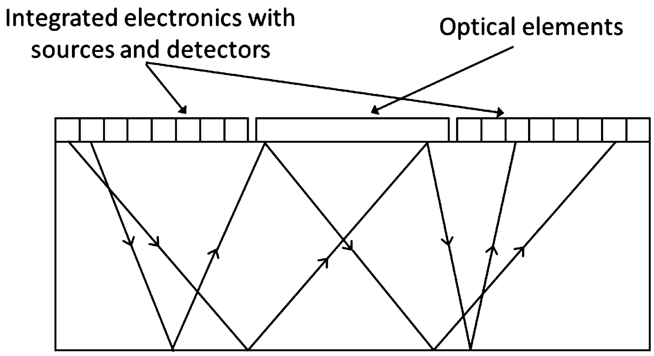

Fig. 12. Planar (folded) optical interconnection architecture. The bottom surface simply reflects the light. The connections are routed by the optical elements.

in many areas. Due to the diversity of forms this takes, it is not possible for us to even approach any level of comprehensiveness in reviewing these areas, and we will have to satisfy ourselves with an illustrative random sampling.

Some of the most important such areas are those involving the capture and display of images, video, and three-dimensional information. Although today most processing of this type of information is performed digitally, optics is naturally involved since it is light emanated or reflected from objects, and ultimately landing on our retinas that creates perception. The traditional conception of a camera is a device that registers signals proportional to the light intensity as faithfully as possible, and a traditional display does the opposite. However, increasingly we see that the optical and computational processes are not seen as independent, but are designed in a mutually aware manner. This can both reduce unnecessary computational burdens and relax requirements on the optical specifications.

Optical information considerations play a significant role in certain types of displays. For instance, there has been significant advances in laser-based displays and projectors. These have been made possible by advances in modulator, microelectromechanical systems (MEMS), and laser source technologies [107]. Near-eye displays [108,109], head-worn displays [110], and light field displays [111,112] have been receiving increasing attention for quite a time. References [113] and [114] are examples of work that particularly well illustrate the use of optical information processing techniques in these applications. These types of displays also find use in virtual reality (VR) and extended reality (XR) [115,116], technologies that are also receiving much attention.

Before moving on we may also mention that the design of diffractive and holographic optical elements [117,118] used for these and other applications also involve principles of information optics. The use of so-called metalenses is an approach to improve over conventional, often bulky refractive or diffractive optical components and to achieve wavefront shaping with nano-scale structures that have thicknesses of the order of the wavelength or below. [119–121]

Another relevant area is three-dimensional video and television [122–124]. While a substantial part of this technology is digital, the image acquisition and display stages inevitably involve optical systems, whose design benefits from optical information processing principles and diffraction theory [125]. Stereoscopic systems are very popular since they are the most straightforward and have a long history [126]. True holographic wavefront reconstruction type displays are the most elegant and definitive approach to recording and playback of three-dimensional images, but progress with this approach has been slow [127–129]. Many works now combine optical information processing principles with computational approaches, for instance [130]. The joint use of optical and computational techniques may be considered representative of a trend that can be expected to increase in importance.

Computational imaging is a term that refers to approaches where computation plays a substantial role in the image formation process [131]. Unlike conventional imaging where we try to obtain a faithful image to begin with and then process it, in computational imaging we are aware of the possibilities offered by possible post-processing and are therefore not constrained to physically form a conventional image. This might include situations where direct imaging is not possible and the information collected has to be solved for to reconstruct the image (as in computerized tomography). It can also include situations where the physical measurement process is imperfect or insufficient, and additional knowledge is introduced to mathematically and/or computationally reconstruct the image. Multidimensional optical imaging is an approach where multidimensional optical measurements including spatial, spectral, temporal information is involved [132,133]. Generally speaking, in these approaches, the optical acquisition becomes integrated with the digital processing and thus physical considerations and optical information processing principles can play an important role [134–137].

Perhaps most intriguing and hard to generalize are situations where optical information processing principles come into play with device and materials principles, possibly involving systems engineered at the nanoscale. Some examples of optical information processing systems based on photonics structures are [138–142].

The way we structure computing systems may undergo substantial changes in the future, in a way that is very difficult to foresee or date (for instance, see [143]). Interest in computing systems that operate on the atomic-scale, based on biological and quantum effects, and depending on varying kinds of individual or collective behaviors of atoms, will likely increase. The qualities of these systems may be very different than those based on a collection of interconnected nonlinear devices that we have today. However, electromagnetic waves remain one of the most fundamental means of information transmission. Since it is desirable to increase the density of information transfer, it seems unlikely that frequencies below the visible would be considered. Higher frequencies can allow even higher densities, and their use would be feasible if suitable sources and detectors are engineered. In any event, these waves would be governed by optical principles over a wide range of frequencies. Thus, although such future computers may take many forms, there is a considerable likelihood that optics will be involved in the percolation of information within them.

It is possible to imagine various computational schemes where atoms or molecules, living or non-living, interact with each other, performing logic operations or otherwise. However, it is important to remember that most interesting computations require global transfer of information, since everything cannot be put next to each other. If information is restricted to interacting only with nearby information, it will take multiple steps for information to reach or affect other far away information it has to interact with. Mass transport is not likely to provide a sufficiently fast means of information transfer either. These considerations provide further support to the preceding paragraph, where we argued it is likely that electromagnetic radiation of at least optical frequencies will be used in future computing systems. This is not to say it is inevitable. The mammalian brain is an example of a computing system that does not internally employ freely propagating electromagnetic radiation for communication.

Given that restricting interactions between parts of a computing system to be local does not seem to be optimal, it seems highly desirable to provide a means of high-speed global communication, which we have argued might best be realized optically. Thus, future computing systems operating at an atomic-scale, based on biological or quantum effects, may benefit from optical interconnections [144].

Optical implementation of neural networks has received attention from the eighties and nineties onward [145–148]. Neural networks are artificial systems inspired by the structure of animal brains. They are very different than common digital computers, which are based on very different principles than animal brains and therefore exhibit very different qualities. Neural networks have a complex network of connections and many operations are realized at once simultaneously. Optics is highly suitable to provide such a parallel and highly connected global network of connections, compared to electrical connections. However, neural networks also involve nonlinear operations that are less readily realized optically, compared to electronic approaches. This suggests a hybrid implementation combining optical and electrical approaches. Thus, designs where the nonlinear part is realized electronically, and the interconnection network is realized optically have been proposed [25]. A notable example of work in this area is the optical implementation of the Hopfield model [149]. Recent notable and highly-cited works provide evidence that optical approaches to neural computation continue to be seen as promising [150–153].

There are many other areas where optical information processing principles remain highly relevant, but which we were not able to cover or even mention. Some noteworthy omissions are optical or photonics systems for biological, medical, sensing, and communications applications (e.g. [154,155]). A very significant area we have totally left outside our scope is quantum optical information processing (e.g. [156,157]).

6. Conclusion

Analog optical information processing (Fourier optics) is a mature field with an established body of knowledge and techniques that is grounded firmly in the science of optics and electromagnetic theory, as well as signal theory, analysis, and processing. Given the widespread availability of cost-effective digital computing, optical processing is likely to be preferred when it offers a unique advantage (such as speed or throughput), or in systems that are inherently optical, including those that are used to acquire or display information.

General-purpose all-optical digital computers may or may not become a reality. However, light may be increasingly used to communicate between the parts of computing systems, at lower and lower levels, making powerful computers possible. Thus we will see light play a greater role in the processing of information as well as its communications, storage, and sensing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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