Concepts of optical signal processing and optical communications

Electronic components allowing to control electric currents with electric currents (or voltages) and integration of a large number of such elements on small silicon chips permitted the development of electronic circuits for analog and digital data processing and their breathtaking evolution over the last few decades, respectively. Analogously, controlling light by light is the key to optical signal processing. Light control by light relies on interaction between two light beams, which is feasible only in the presence of a nonlinear optical effect.

The nonlinear index of refraction (optical Kerr effect) appears to be one of the most promising optical nonlinearities for use in creating the basic elements of future optical computers.

All-optical switching, optical transistor

One of the conceptually most simple realization of an all-optical switch is the nonlinear Mach-Zehnder interferometer containing a medium with a nonlinear index of refraction (Fig. IV-9). The transmittivity of this system for the input light beam (signal beam to be controlled) is given by

$$T_{\rm MZ} \left(I_{\rm control} \right) = \frac{1}{2} + \frac{1}{2} \cos \left(2\pi \frac{L}{\lambda_0} n_2 I_{\rm control} + \varphi_0 \right) \tag{IV-105}$$

where *L* is the interaction length of the (weak) input beam and the (strong) control beam in the active medium of nonlinear index n_2 and $I_{control}$ stands for the intensity of the control beam. Depending on the bias phase φ_0 and the magnitude of $I_{control}$, this system may serve as an *on-off switch* or as an *amplitude modulator*. the intensity of the signal beam at the output can be switched on and off or modulated by the temporal variation of $I_{control}$. The concept can also be implemented in an anisotropic nonlinear optical fibre with the legs of the interferometer and the output mirror being played by two polarizations and a polarizer, respectively (Fig. IV-10).



We may also use a nonlinear Fabry-Perot interferometer (a nonlinear medium sandwiched between two mirrors of reflectivity *R* that are aligned normally to the optical axis of the signal beam) for the same purpose. The transmittivity of this device can be written as

$$T_{FP}(I_{\text{control}}) = \frac{1}{1 + (2F/\pi)\sin^2 \left[2\pi \frac{L}{\lambda_0} n_2 I_{\text{control}} + \varphi_0\right]}$$
(IV-106)

where $F = \pi R^{1/2}(1-R)^{-1}$ is called the *finesse* of the interferometer. For a high value of *F* a small variation of the intensity of the control beam can result in a large variation in the *T*_{FP} and hence in the intensity of the transmitted signal beam, which implies a high differential gain and constitutes an *optical transistor*.

Bistable optical devices

A bistable (or two-state) system has an output that can take only one of two distinct stable values, no matter what input is applied. Switching between these values may be achieved by a temporary change of the level of the input (Fig. IV-11).





Sophisticated digital electronic systems contain a large number of interconnected basic units: switches, logic gates and memory elements (flip-flops), which are based on bistable circuits. The bistable optical devices to be discussed below can – similarly to their electronic counterparts – be used as optical gates and flip-flops as the basic building blocks for future optical computers.

Optical bistability can be achieved if the output of an all-optical switch (e.g. a nonlinear interferometer discussed above) is fed back (by use of mirrors, for example) to control the transmission of the switch (Fig. IV-12).



If it is the output intensity I_0 that controls the transmittivity T of the device, we arrive at the relationship $I_0 = T(I_0)I_i$, which yields the input-output relation for a bistable optical system as

$$I_{i} = \frac{I_{o}}{T(I_{o})} \tag{IV-107}$$

If $T(I_0)$ is a nonmonotonic function, such as the bell-shaped function shown in Fig. (IV-13a), I_i will also be a nonmonotonic function of I_0 , implying that I_0 will be a multivalued function of I_i , as illustrated in Fig. (IV-13b,c). The system therefore exhibits a bistable behaviour as depicted in Fig. IV-14.





According to Eqs. (IV-105) and (IV-106) both the nonlinear Mach-Zehnder interferometer and the nonlinear Fabry-Perot interferometer exhibit a transmittivity that is a nonmonotonic function of the intensity of the control beam, hence use of the output beam (or a fraction of it) as a control beam (Figs. IV-15 and IV-16) by means of a suitable optical feedback results in the bistable behaviour qualitatively sketched in Figs. IV-13 and IV-14.



Fig. IV-15



Optical interconnections, analog signal processing

In electronic computing systems interconnections are made by use of conducting wires, coaxial cables or conducting channels within integrated circuits. Optical interconnections may similarly be realized by use of integrated optical waveguides. However, it appears to be much more powerful to implement interconnections by free-space light beams, an option that does not exist in electronics. Conventional optical components (e.g. lenses, prisms) are used in numerous optical systems to establish optical interconnections with unparalleled density (up to 1000x1000 points/mm² achievable; a million nonintersecting and properly insulated wires or channels would be required for this to be implemented electrically!!) and may be used to create interconnecting maps with simple patterns (Fig. IV-17).



Fig. IV-17

Another unique feature of optical interconnections is that interconnection maps can also implement analog computing operations. *Multiplication* is achieved by transmitting the light through a transparency or a modulator, in coherent processors the complex amplitude is multiplied by the complex amplitude transmittance of the transparency. *Addition* is achieved by routing beams to the same point in the output plane. With the combination of these two elementary operations a number of discrete and continuous operations are feasible with simple optical components such as spherical and cylindrical lenses.



Fig. IV-18

A Fourier-transform (up to two dimensions) can also be implemented by a simple *f*-to-*f* imaging (Fig. IV-19). The recognition of optical wave propagation leading to a Fourier-transform in a natural manner has played an important historic role in motivating the use of optics for signal processing and computing.



Fig. IV-19

The Fourier-transform capability of an optical interconnection map enriches further the list of mathematical operations that can be performed in analog optical processing. These include differentiation, convolution and cross-correlation

$$\frac{\partial}{\partial x} f(x, y) \implies ik_x \cdot F(k_x, k_y)$$

$$g(x, y) = \iint f(x', y') h(x - x', y - y') dx' dy' \implies H(k_x, k_y) F(k_x, k_y)$$
(IV-108)

A large stock of discrete and continuous mathematical operations on arrays of variables or on two-dimensional functions may be realized by combinations and cascades of the above operations. The power of optical analog processors lies in the high-degree or parallelism and the large size of interconnection maps. On the negative side, analog computing has a reduced accuracy and dynamic range (as compared to digital one) and is suitable principally for computational tasks that are insensitive to error. Promising application fields include broadband signal processing, radar signal processing, image processing and machine vision, artificial intelligence and neural networks.

Computer-generated holographic transparencies (or reflectors) constitute the most powerful and most general technology for creating high-density optical interconnection maps. Here it is utilized that a phase grating $\exp(ik_x x + ik_y y)$ causes a tilt of the transmitted (or reflected) plane wave by angles $\sin^{-1}k_x/k \approx k_x/k$ and $\sin^{-1}k_y/k \approx k_y/k$ as illustrated in Fig. (IV-20).



A general holographic interconnection map can now be created by an array of phase gratings of different periodicities and orientations as depicted in Fig. (IV-21). If the grating segment located at position (x, y) has frequencies $k_x = k_x(x, y)$ and $k_y = k_y(x, y)$ and $k_y(x, y)$ and $k_y = k_y(x, y)$ and $k_y(x, y)$ and $k_y($

 $k_y(x,y)$ the angles of tilt are approximately k_x/k and k_y/k so that the beam transmitted or reflected by the transparency at position (x, y) hits the output plane at a point (x', y') satisfying

$$\frac{x'-x}{d} = \frac{k_x}{k}, \quad \frac{y'-y}{d} = \frac{k_y}{k}$$
(IV-109)
$$= i^{\varphi(x,y)}$$
Fig. (IV-21)

Optical interconnections in microelectronics

Advances in high-speed high-density microelectronic circuitry and the emergence of parallel processing architectures have created communication bottlenecks so that interconnections have become a major problem. In very-large-scale integrated circuits (VLSI), interconnections occupy a large portion of the available chip area. Optical interconnections offer a number of basic advantages over their electronic counterparts in terms of

- Density: 3D instead of 2D, no need for insulation.
- Delay: delay always 3.3ps/mm, in electronics inversely prop. to capacitance/length, which depends on the number of interconnections branching from an interconnect
- Bandwidth: density not affected by bandwidth requirements in contrast with electrical
 Interconnections
- Power: impedance matching in electronics consumes a lot of power, in optical interconnections, only the electric-to optical and optical-to-electric conversion efficiencies determine the power requirements

These advantages have led to a great deal of r&d efforts aiming at replacing electrical with optical interconnections in microelectronics. A possible optical interconnection architectures using lights sources (LEDs or diode lasers) and electro-optic modulators are depicted in Figs. IV-22 and IV-23. A hologram may route an external light source to detectors on a chip for clocking purposes as shown in Fig. IV-24.



Fig. (IV-22)









All-optical digital computing

An optical digital computer can be built by mimicking the electronic digital computer in that electronic gates and memory elements are replaced by optical ones and electronic interconnections are replaced by waveguides in integrated optics. However, such an approach would not exploit some basic differences between photonics and electronics, which could give photonics decisive advantages.

A large number of points in two parallel plains can be optically interconnected by a large 3D network of free-space global interconnections established by use of a custom-made hologram. Using this technical capability, one might envisage an optical computing system in which a two-dimensional array of *N* optical gates ($N = 10^6$, for example) are interconnected holographically (Fig. IV-25). The machine could be programmed or reconfigured by changing the interconnection hologram. The level of parallelism is many orders of magnitude higher than conceivable with electronic processors.



Fig. IV-25

This capability for ultrahigh-degree of parallelism comes together with the potential of much higher speed and lower switching energy of optical gates as depicted in Fig. IV-26.

Ultimate speed limits of optical signal processing



Fig. IV-26

In optics, pulses with durations down to 10fs are available for switching operations, orders of magnitude shorter than the shortest electrical pulses. To exploit this potential, however, we shall have to address broadband optical pulse propagation, which we shall do at the end of this chapter.

Potentially, the switching energy of optical gates can be as low as attojoules, again, orders of magnitude lower than in semiconductor electronics. Analysis of the ultimate switching energy requires quantization of the electromagnetic field and we will return to this question in the framework of quantum optics. Exploitation of the above degree of parallelism $N = 10^6$, operations in parallel and a switching time of 100fs would result in 10^{19} bit operations per second. This would exceed the processing speed of the human brain by approximately a factor of a thousand and the largest currently available electronic computer by many orders of magnitude.

Optical communications

Until recently, virtually all communications systems have relied on the transmission of information by radio-frequency (rf) and microwave signals over electric cables or on rf and microwave electromagnetic radiation propagating in free space. This is remarkable because light appears a more natural choice as a carrier of information given the fact that – unlike radio waves – it did not have to be discovered. The lack of light sources with the capability of switching on and off radiation at a high rate and the lack of low-loss transmission systems delayed the development of this technology by more than hundred years with respect to the invention of the light bulb, the first electrically controlled light source. The recent spectacular advances of fibre-optic communications have their roots in two critical inventions: (i) the development of semiconductor-based incoherent and coherent light sources (LEDs and diode lasers, respectively) and (ii) the development of ultralow-loss optical fibers.

The generic lay-out of a fibre-optic telecommunication systems is shown in Fig. IV-27.



Fig. IV-27

Key technologies in optical information transmission include multiplexing and light modulation. Multiplexing is the transmission and retrieval of more than one signal through the same communication link. The most-widely-used approach is currently wavelength-division multiplexing (WDM), in which carriers of distinct, well-separated wavelengths are modulated by different signals to be transmitted (Fig. IV-28). At the receiver, the signals are identified by use of filters tuned to the carrier wavelengths (Fig.

IV-29).





The information carried by the optical wave is most-frequently transmitted in the form of a sequence of binary bits, "1" and "0". Depending on the type of modulation used, these bits can be represented by

• the presence or absence of light: on-off keying (OOK)

or

• two distinct values of the frequency: frequency-shift keying (FSK)

in a sequence of time-slots as depicted in Fig. IV-30.



Fig. IV-30

The information transmission rate in units of bit/s is equal to the inverse of the time slots carrying 1 bit information:

Data transmission rate [in bit/s] =
$$\frac{1}{\text{Duration of time slot/bit}}$$
 (IV-110)

The shorter the time slot needed for transporting 1 bit information (henceforth briefly: carrier duration) the larger amount of information can be transmitted per unit time. Propagation effects set a limit to the shortest carrier duration in fibre-optic communication systems. The most severe effect limiting the carrier duration is related to the broadening of a wavepacket due to a frequency-dependent group velocity, which is briefly referred to as *dispersion*. Dispersion has different sources and magnitudes in different types of fibers shown in Fig. IV-31.





The most important parameters of a dielectric waveguide with circular symmetry (briefly: fibre) are the refractive indices of the core and the cladding, n_1 and n_2 (< n_1), respectively. In general, light can propagate in a number of different *modes* in the optical waveguide, which possess different transverse field distributions. The number of modes guided is determined by the fibre *V* parameter

$$V = 2\pi \frac{\partial}{\lambda_0} \sqrt{n_1^2 - n_2^2} \approx 2\pi \frac{\partial}{\lambda_0} n_1 \sqrt{2\Delta}$$
 (IV-111)

where a is the core radius and $\Delta = (n_1 - n_2)/n_1$ is the fractional refractive index change, which is usually very small (weakly guiding fibre), $\Delta = 0.001$ to 0.02.

Step-index fibre with V >> 1. A large number of modes ($M \approx V^2/2$) can propagate (*multi-mode fibre*), each of which has a different group velocity satisfying

$$\frac{c}{n_{\rm l}} (1 - \Delta) \leq V_g \leq \frac{c}{n_{\rm l}} \tag{IV-112}$$

When a light pulse is guided in many modes of different group velocity and travels a distance *L*, it undergoes different delays, leading to a spreading over a time interval

$$\Delta \tau \approx \frac{L}{c} n_1 \Delta \tag{IV-113}$$

Which is referred to as *modal dispersion* of the fibre.

For a graded-index fibre with V>>1 and parabolic index profile one obtains

$$\Delta \tau \approx \frac{L}{c} n_1 \frac{\Delta^2}{2} \tag{IV-114}$$

Hence the modal dispersion of a graded-index fibre is by a factor of $\Delta/2$ smaller than that of a corresponding step-index fibre.

Single-mode fibers are characterized by V < 2.405 (the smallest root of the Bessel function \mathcal{A}) and guide all the light in a single mode of well-defined group velocity. Hence modal dispersion is eliminated. Pulse broadening merely occurs due to the finite optical bandwidth of the wave because the group velocity is wavelength dependent. A short optical pulse of spectral width $\Delta\lambda$ spreads to a temporal width

$$\Delta \tau \approx |D| \Delta \lambda L \tag{IV-115}$$

where *D* is the dispersion coefficient in units of (ps)(km)⁻¹(nm)⁻¹. At the wavelength of $\lambda_0 = 1.55 \,\mu$ m, where the attenuation of the fused-silica fibre is minimum (0.16dB/km), the dispersion is $\approx 20 \,\text{ps/km-nm}$ (Fig. IV-32). Hence a light pulse with an initial duration of 10 ps and bandwidth of $\approx 0.4 \,\text{nm}$ ($\lambda_0 = 1.55 \,\mu$ m would broaden to $\approx 800 \,\text{ps}$ after travelling a distance of 100 km down a single-mode fibre.



Fig. IV-32

This effect appears to introduce an ultimate limitation to the minimum carrier duration and hence maximum data transmission rate applicable for communication over a certain distance to be bridged without signal refreshment (by repeaters). The analysis in the next section aims at showing how this apparently ultimate limitation in optical telecommunication can be overcome by exploiting linear and nonlinear propagation effects in optical pulse propagation in fibers.