INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

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Second Winter College on Optics

20 February - 10 March 1995

Optical Computing

P. Chavel

Institut d'Optique
Orsay, France

OPTICAL COMPUTING

Pierre CHAVEL
INSTITUT D'OPTIQUE (IOTA)
CNRS, ORSAY, FRANCE

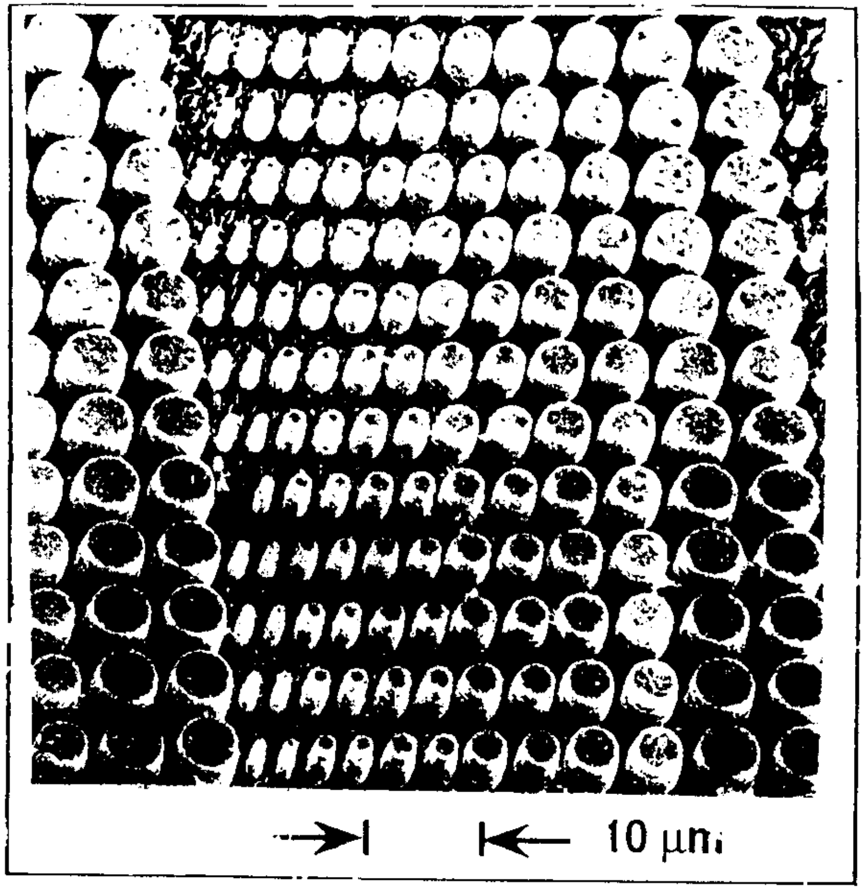
OUTLINE

- Devices
- Operations with optics:
  - scalar product
  - matrise-vector product
  - convolution
- Optical processors
  - Optical correlators, computers, cellular automata
- Optical interconnects

The first transistor (Bell Labs 1948)

The first optical devices for computing?
for connections?
for fast, smart telecom.? (Sc & Technol 1988)

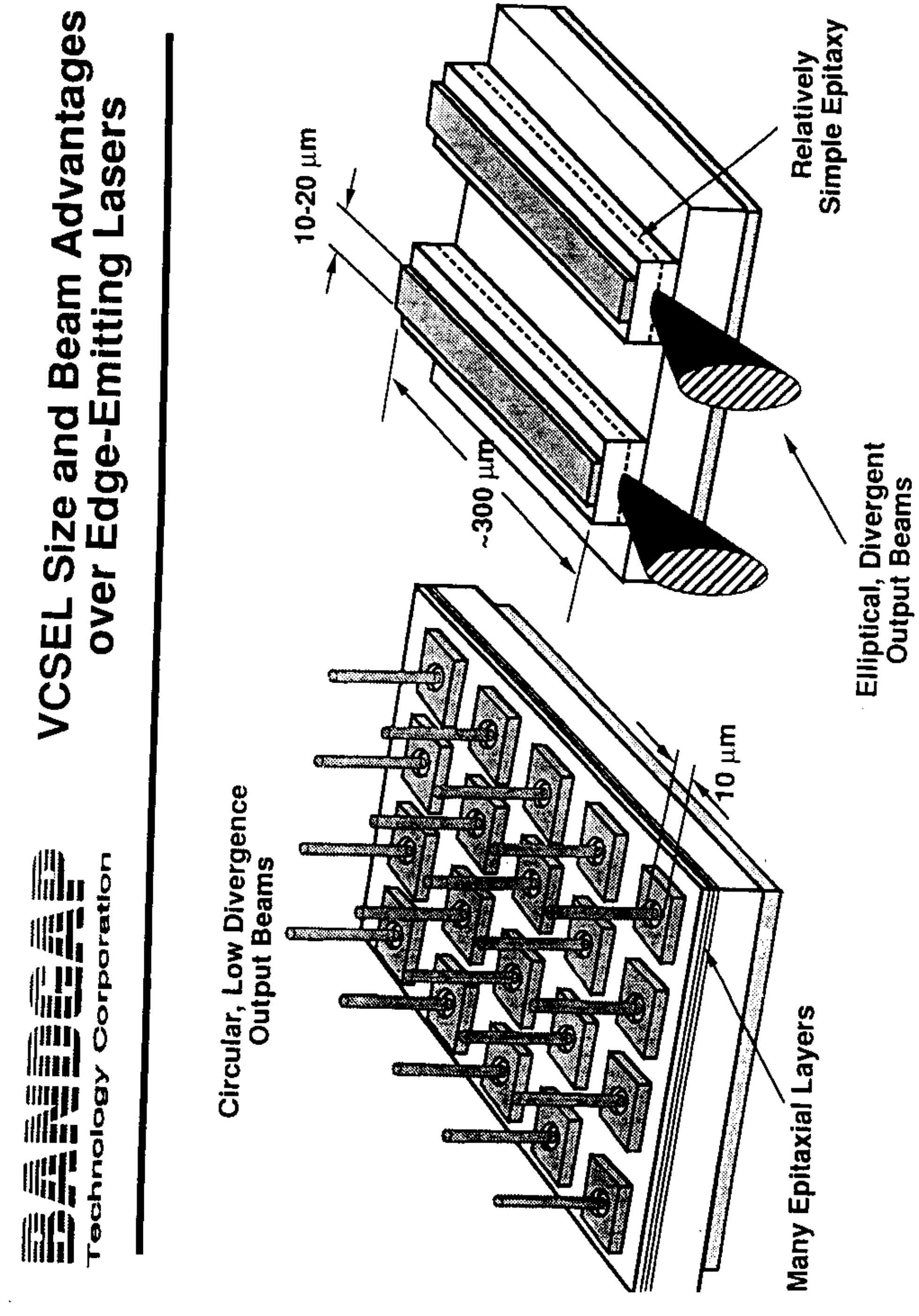
.... ≃ 1990?



Scanning electron micrograph of a small portion of the μ-laser array. Jewell et al., ATT Bell, 1989

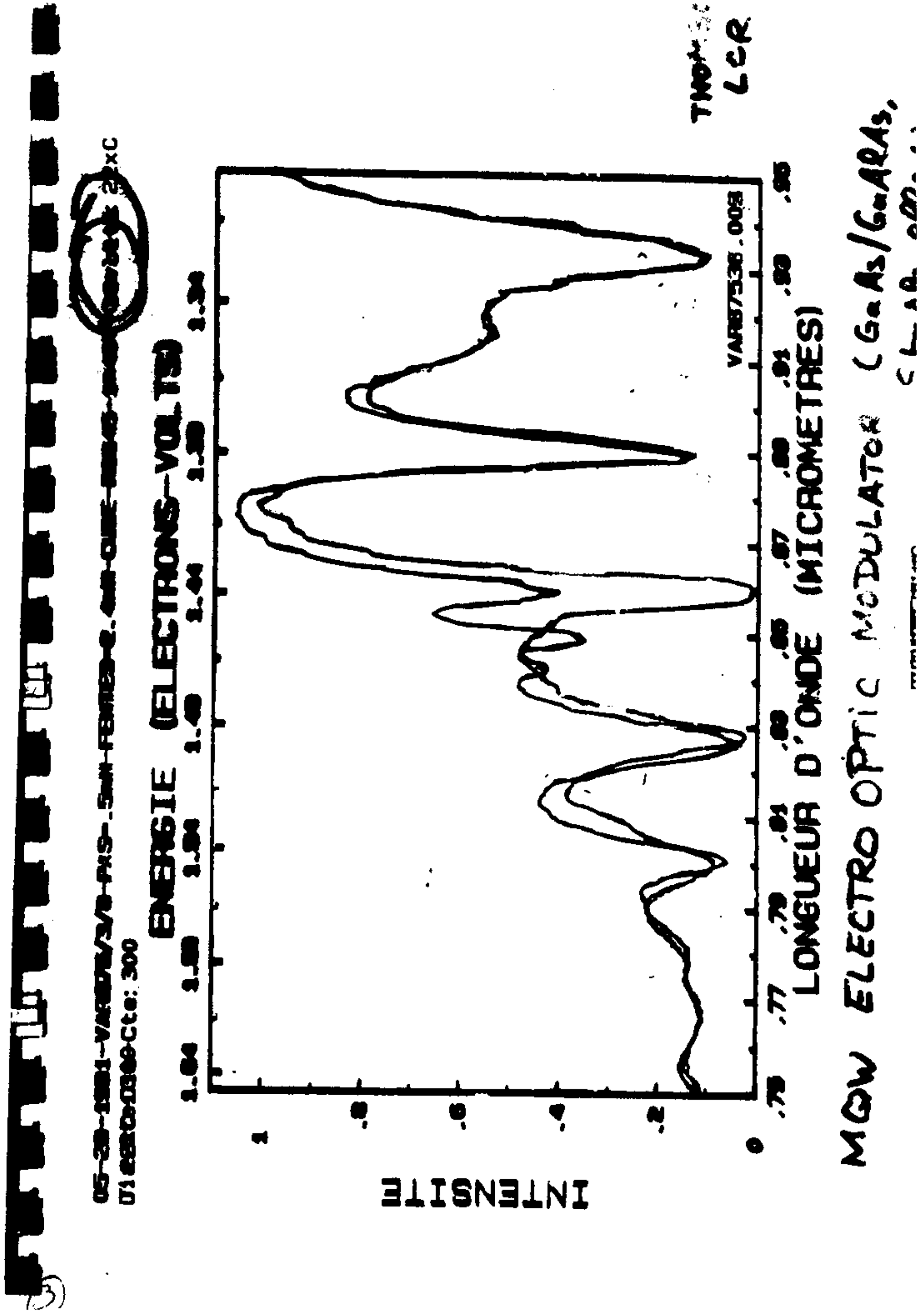
2 000 000 de lasers sur 1 cm²

(2)



CNET Bagneux 1994.

Scanning electron micrograph of 4-μm-diam microresonators.



INPUT DEVICES

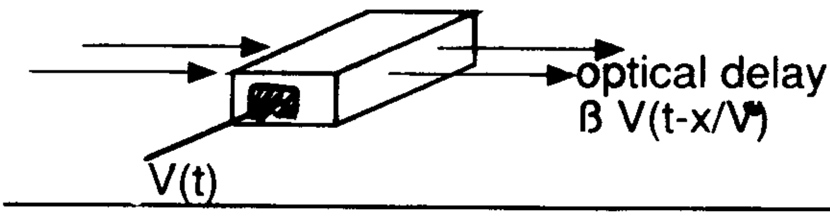
Liquid crystal displays (input can be electronic or optical)

512x512, 1/25s, F.T. : 10^8 operations/s

ferroelectric liquid crystals are 100 times faster

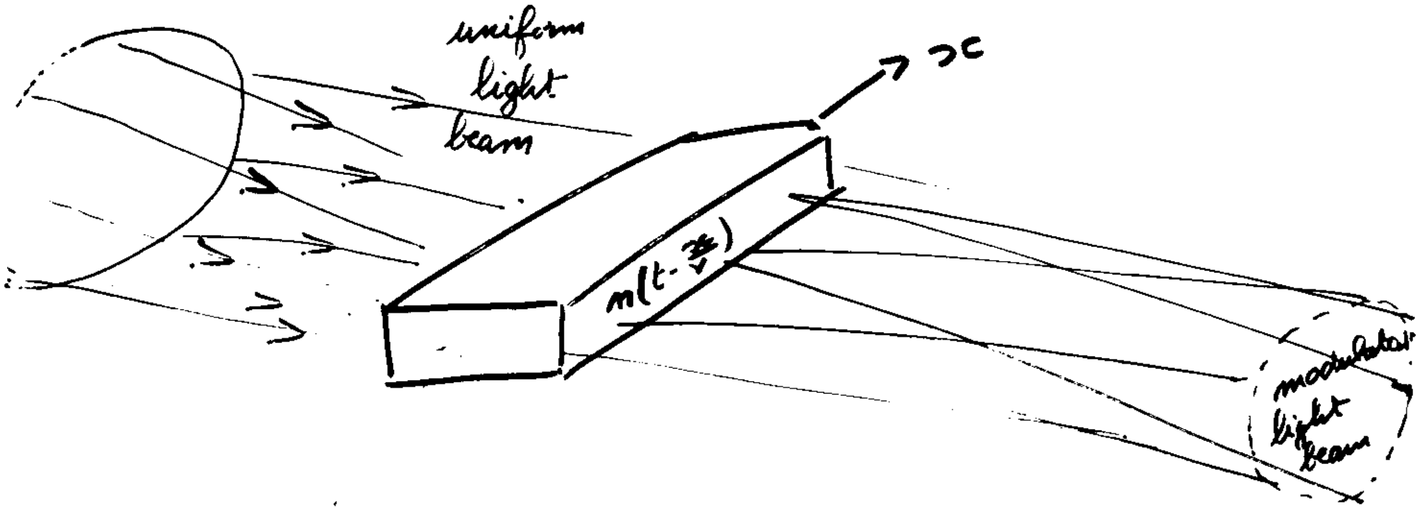
Acousto-optic modulators

1000 points, 1µs, 1-D F.T. : 10^{10} operations/s



5

ACOUSTO-OPTIC MODULATORS/DEFLECTORS



bandwidth 1 GHz

transit time 1 µs

NEWS AND COMMENTARY FOR THE INTERNATIONAL OPTOELECTRONICS INDUSTRY

OE REPORTS

Published by SPIE—The International Society for Optical Engineering

[redacted]

Acousto-optics:
From AOTFs to optical computers?

by Albert Tebo

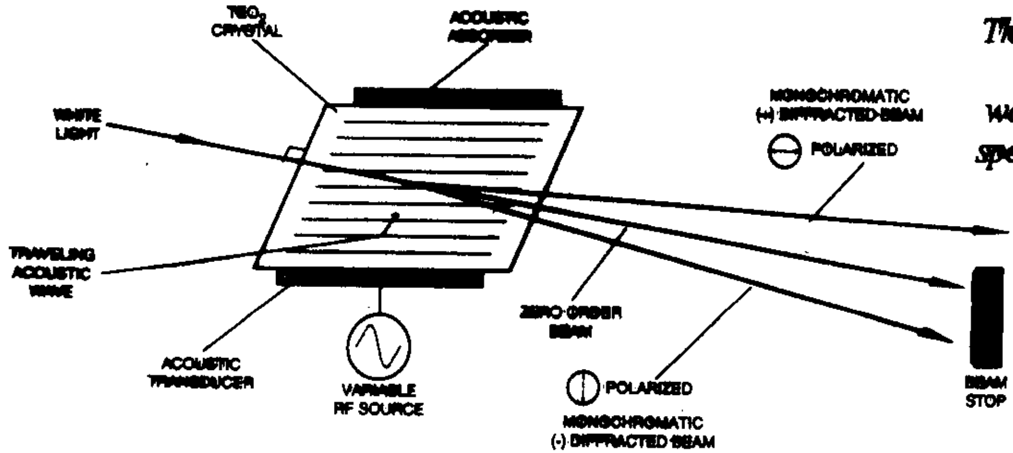


FIGURE 1. SCHEMATIC REPRESENTATION OF A NON-COLLINEAR AOTF. COURTESY OF THE BRIMROSE CORPORATION OF AMERICA.

The acousto-optic tunable filter (AOTF) has become the workhorse of spectroscopy and spectrometry. But developments in acousto-optics are opening up many new applications for AO devices.

Acousto-optic devices use ultrasound to alter the refractive index of an optical medium such as a crystal. This means the devices can control the phase, amplitude, frequency, and angular direction of a laser beam.

Alternatively, the ultrasound—acoustic waves at radio frequency (RF)—can be used (5)

of the crystal, cause variations in the refractive index of the crystal.

This results in the diffraction of a monochromatic beam of light out of the main (zero order) beam, the wavelength of which can be selected by changing the frequency of the applied RF. See Figure 1. In operation as an

ness—no moving parts; (f) ideal for use with a lock-in (phase-sensitive) amplifier.

An article in "SDI High Technology Update," Vol. 2 #4, 1993, indicates that AOTFs are finding their place in a variety of applications:

- a spectrometer that monitors changes in the

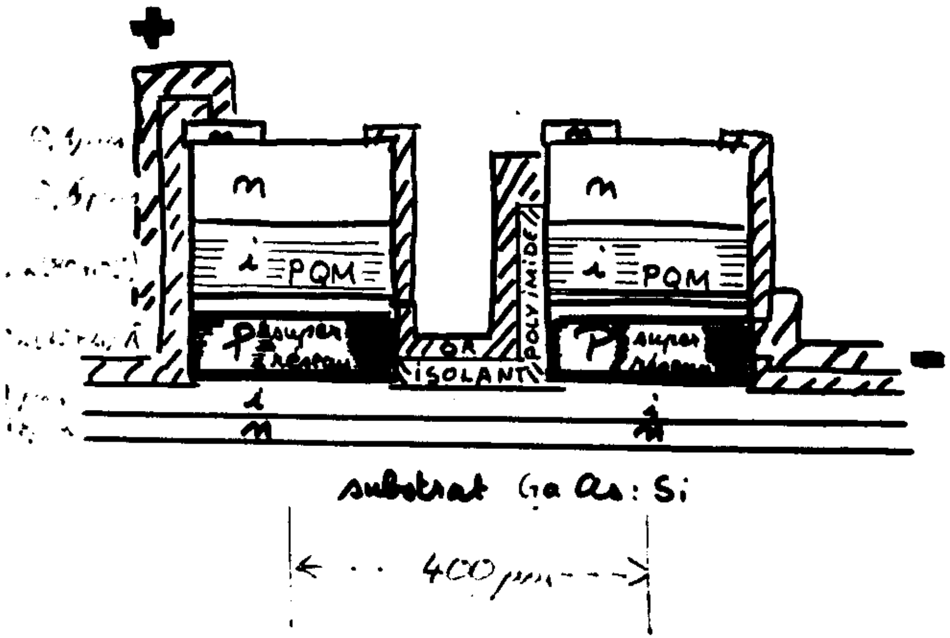
S-SEED

ATT Bell

STRUCTURE

(GaAs, GaAlAs, dopants)

"symmetric - self electrooptic effect device"



D.A.B. MILLER
ApPhysLet 45 13 (1884)

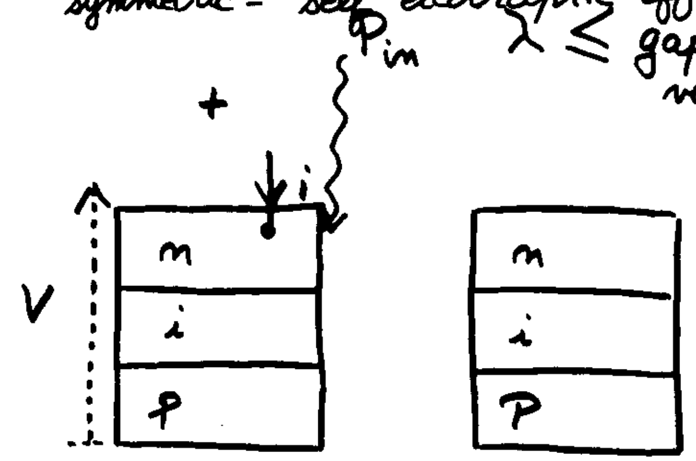
S-SEED

ATT Bell

caractéristiques photoélectriques

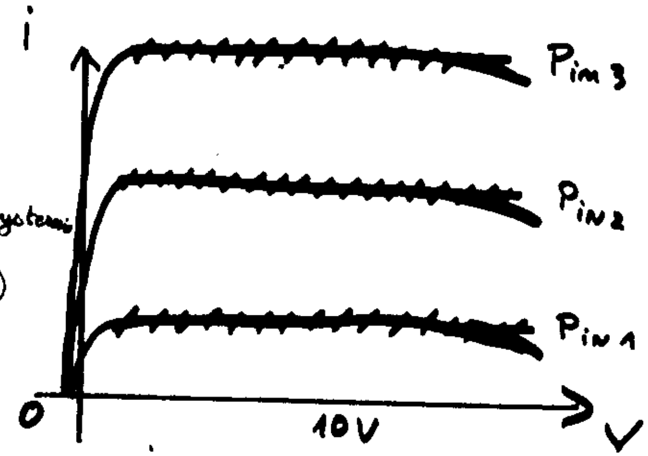
"symmetric - self electrooptic effect device"

$\lambda \leq$ gap GaAs vers 0,85µm

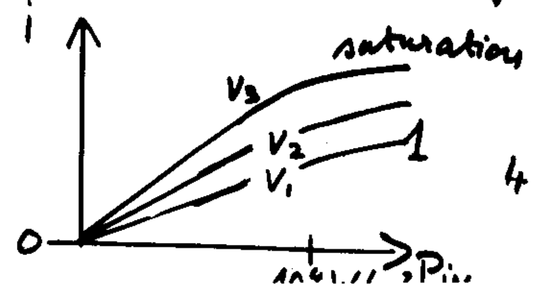


(NB en fait il y a hysteresis sur le palier)

hysteresis on the plateau



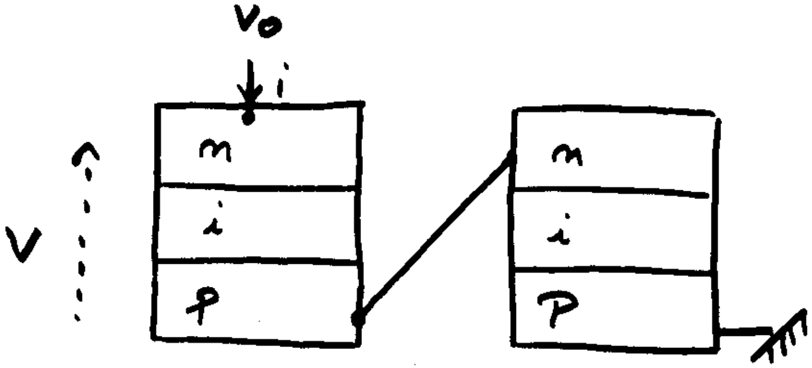
$S \simeq 0{,}3$ A/W

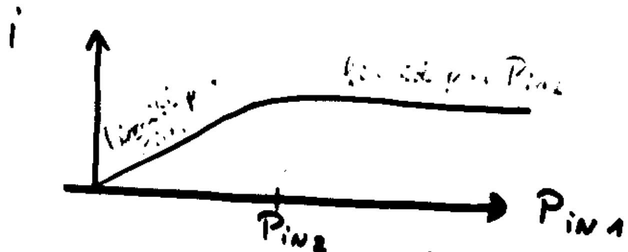


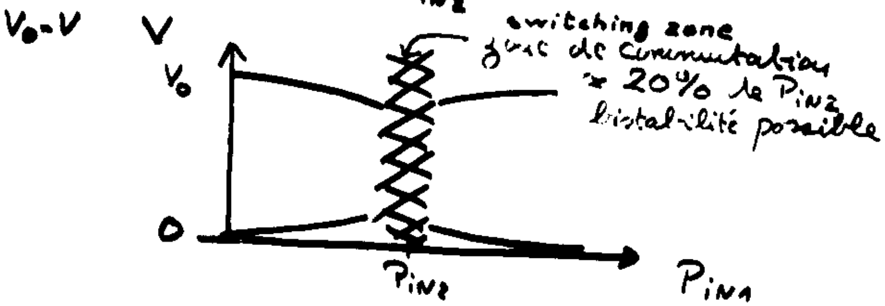
S-SEED

caractéristiques de commutation électrique (ATT Bell electrical switching)

"symmetric - self electrooptic effect device"







A.T.&T. Bell Labs' "S-SEEDs"

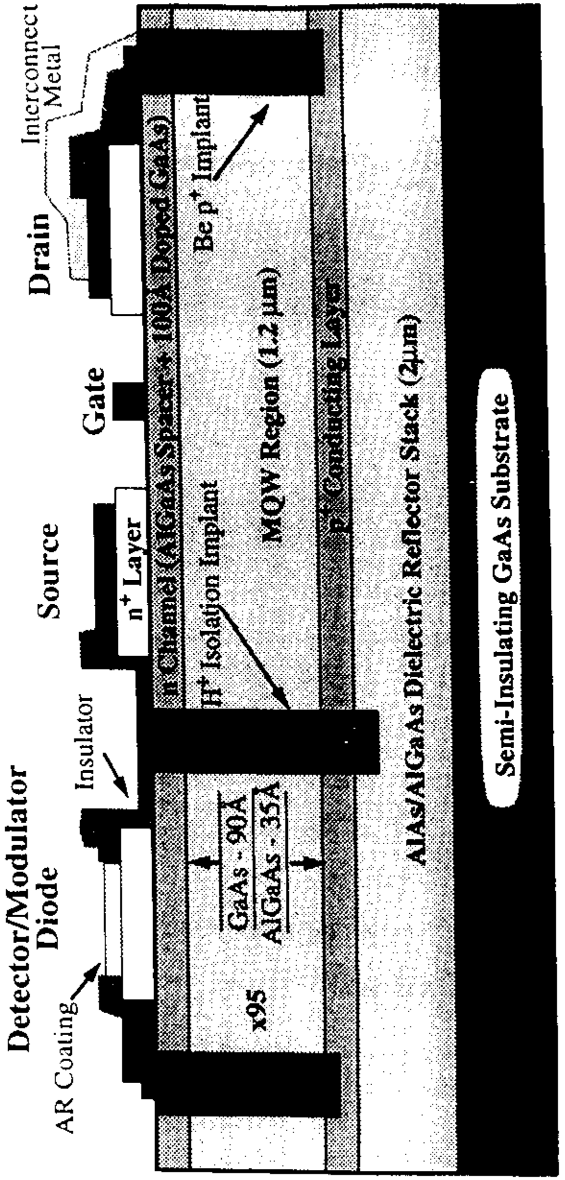
32 x 64 matrices of electrooptic, nonlinear MQW-photodiode pairs

available commercially

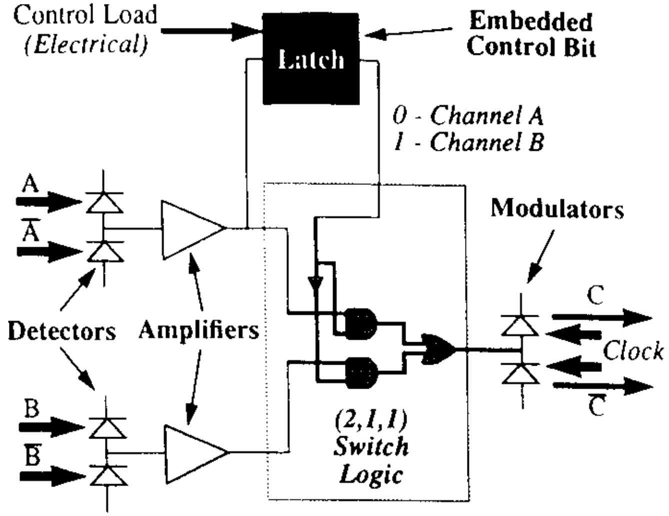
switching energy ~1 pJ / µm² — CMOS 10 …/µm²

switching time { optical < ns ; RC limited → id.

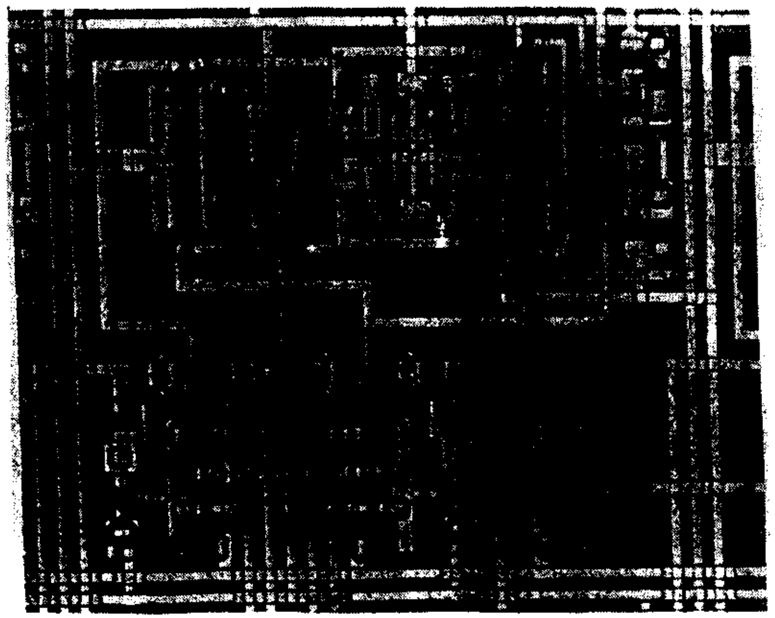
- still way behind microelectronics
- recent progress considerable
- limits yet out of sight (why should they be different from those of microelectronics?)



FET-SEED layer structure.



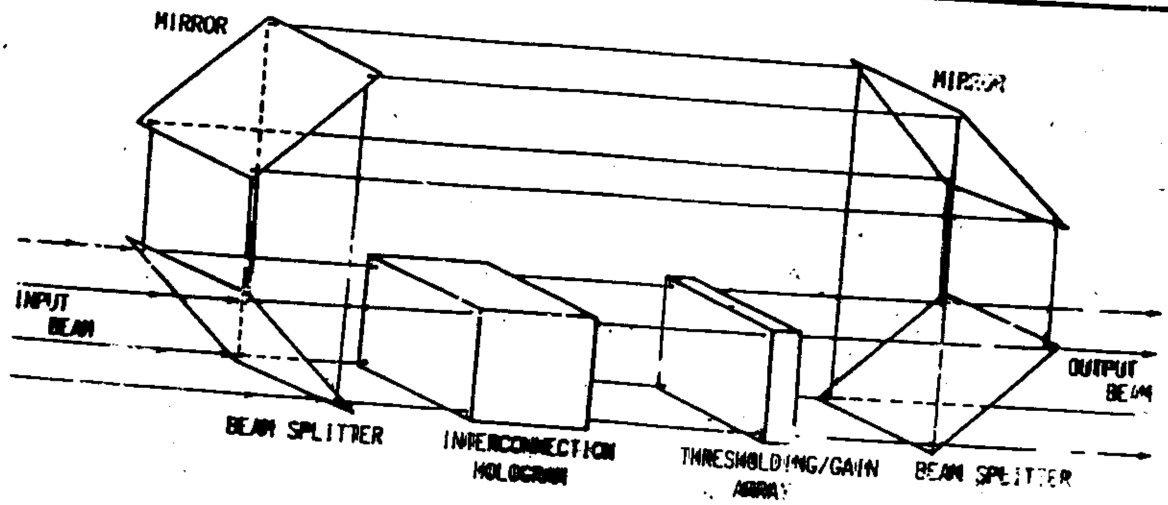
(a)



(b)

*System*₅ FET-SEED-based embedded control node. (a) Schematic. (b) Picture.

ONE POSSIBLE "ULTIMATE" OPTICAL COMPUTER

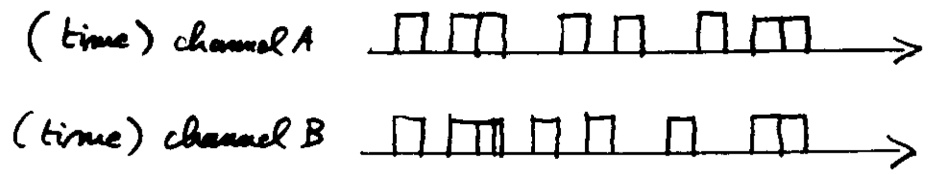


~ (10^6 ARRAY ELEMENTS)/(100 PS LOOP TIME) ~ 10^{16} OPS/SEC
~ MANY [illegible]-EQUIVALENT COMPUTERS

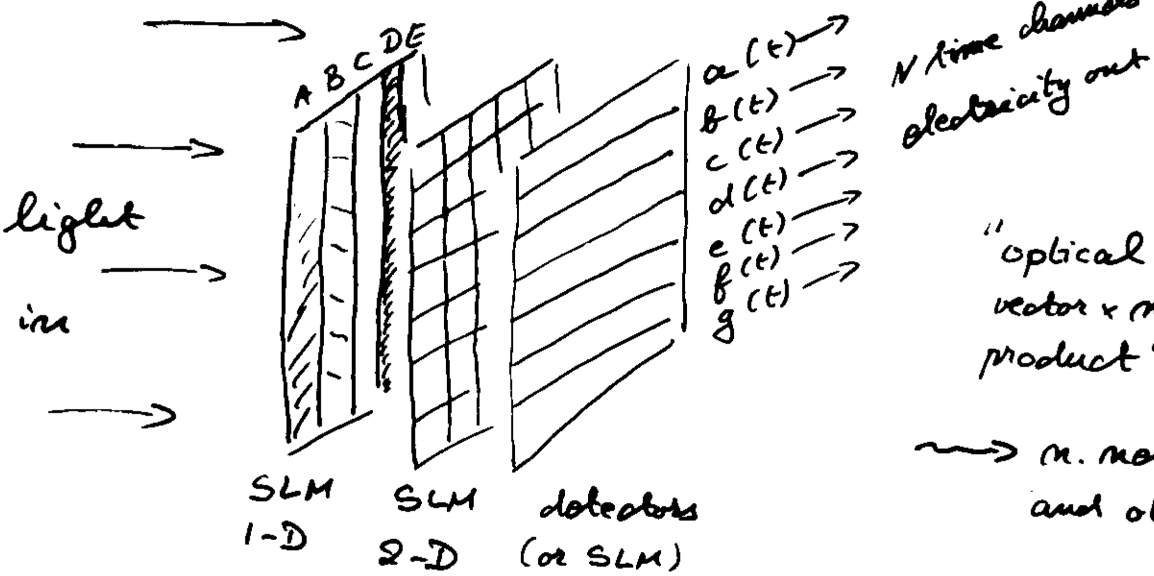
University of DAYTON Research Institute
and many others around 1985

ON THE PHILOSOPHY OF OPTICAL COMPUTING (A)

	DIGITAL	vs ANALOG
COMPUTING IN GENERAL	• accuracy • universality: 3 operations are enough: 1) O. interconnects ? 2) O. logic ? 3) O. memory ?	• economy (hardware)
OPTICAL COMPUTING	↑ ?	→ O. Convolutions, correlations (O. Matrix x vector)

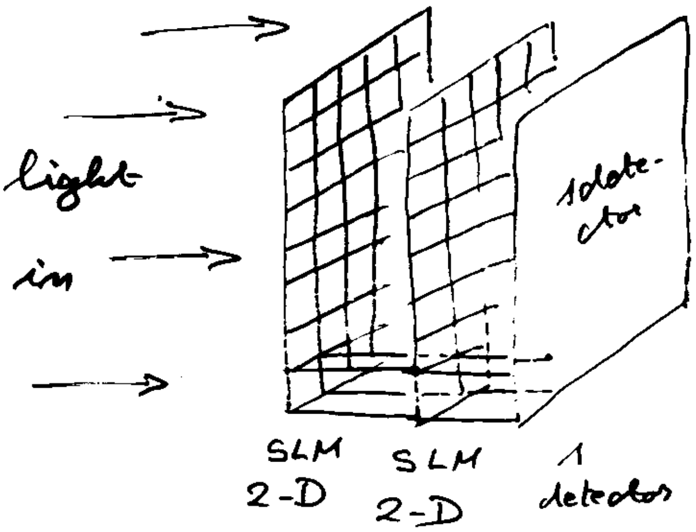


1 light beam = scalar product in time

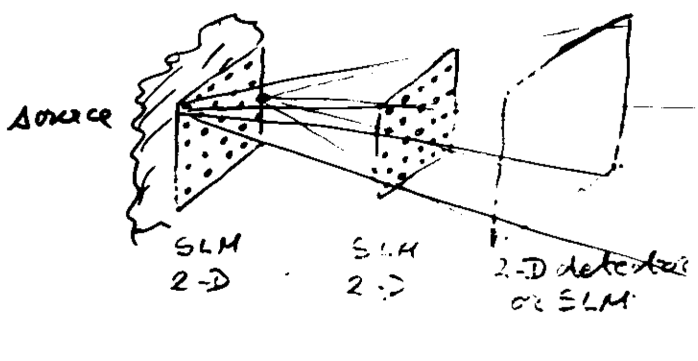


"optical vector x matrix product"

⟶ n. nets and others



scalar product of images



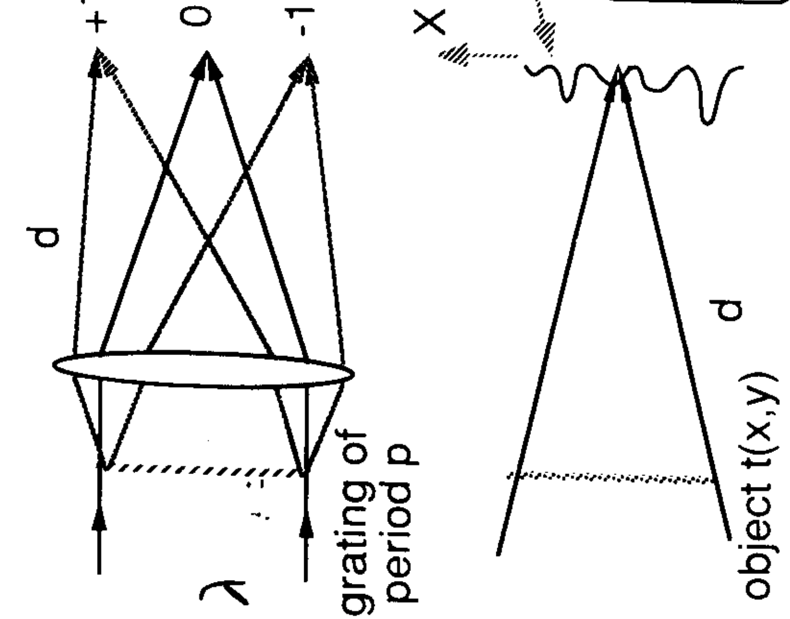
convolution (/correlation) = many scalar products.

analog processors

DIFFRACTION GRATINGS AND THE OPTICAL F.T.

+1 diffracted peak at $\lambda d/p$

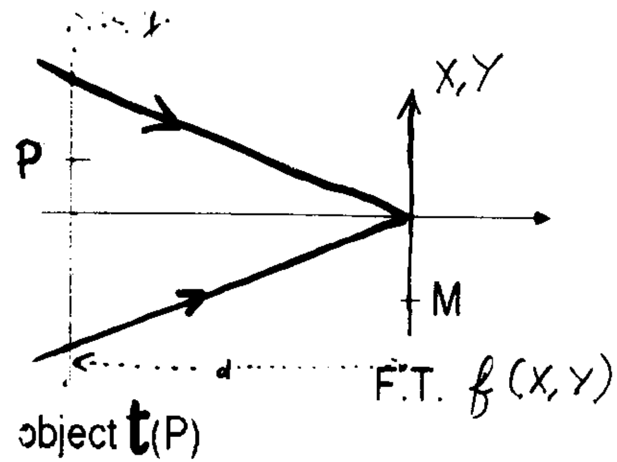
spatial frequency $1/p_x$, $1/p_y$ at $\lambda d/p_x$, $\lambda d/p_y$



computing power
10^{12} analog, weighted interconnects
(specialized operation)
problem : "real time" I/O

2 cont'd

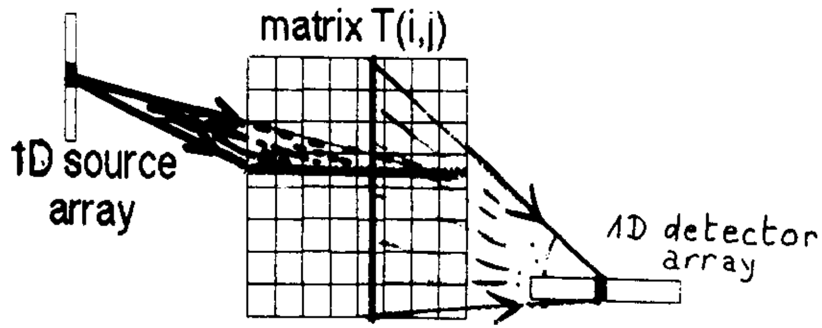
~~the~~ optical Fourier transform

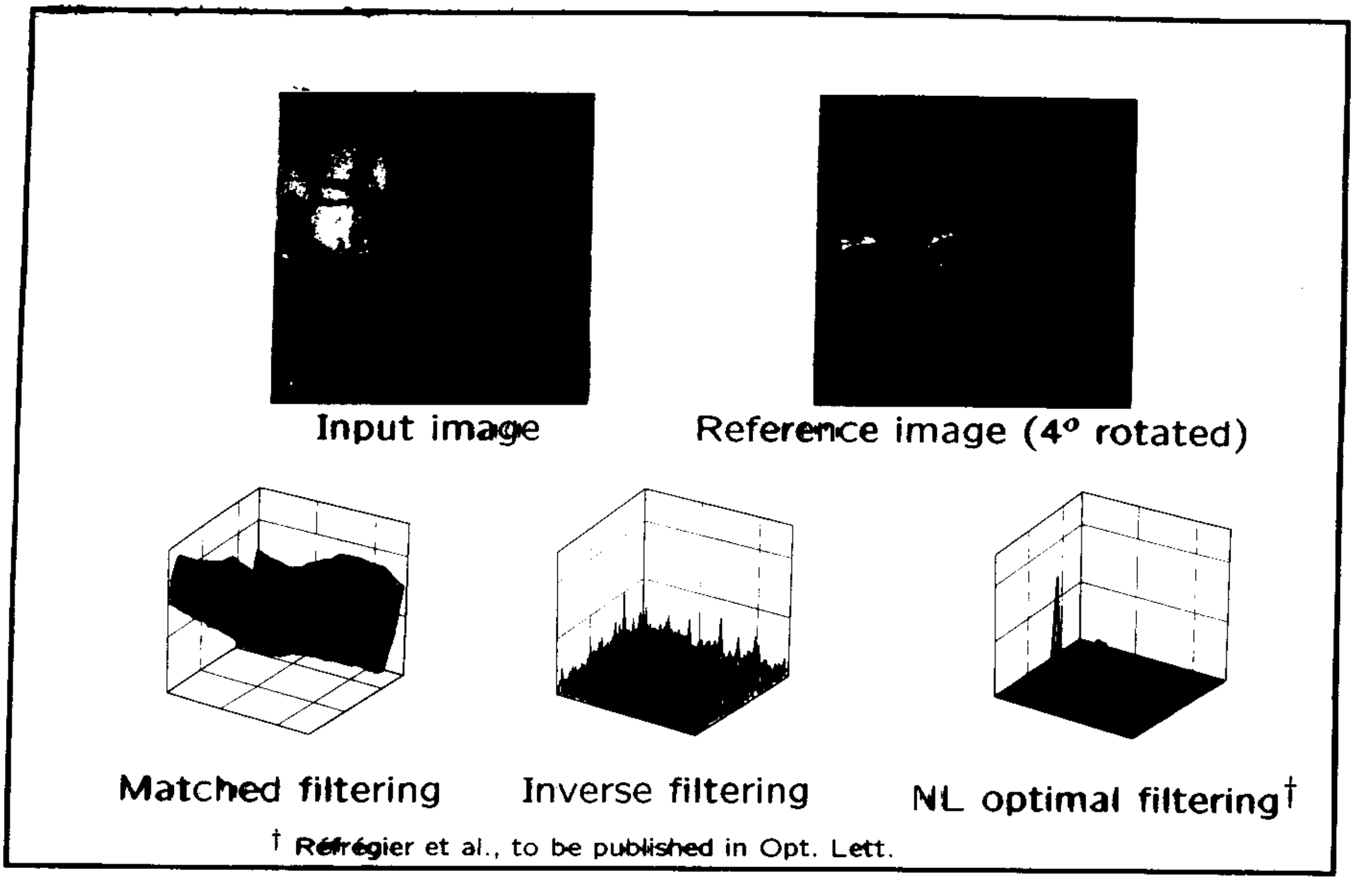


typically worth 10^{12} interconnects (weighted, analog)

$$f(X,Y) = \alpha \int_{-\infty}^{+\infty} t(x,y) \exp -2i\pi \frac{xX + yY}{2\lambda d} \, dx \, dy$$

-optical matrix multiplication (analog)





THOMSON-CSF
Laboratoire Central de Recherches

(12)

Ph. RÉFRÉGIER
V. LAUDE
1993

ON THE PHILOSOPHY OF OPTICAL COMPUTING (2)

General purpose vs dedicated machines

e⁻ machines are
- cheap
- reliable
- available
- and people are used to them

there is no more challenge
here for optics. ⟹ try dedicated ?

[illegible] that [illegible]
[illegible] in [illegible]

[illegible] VISION [illegible]
[illegible] they can be [illegible]
[illegible] ⟹ OPTICALLY ASSISTED
IMPLEMENTATION [illegible]

ANALOG: CONVOLUTION

O. convolution works (e⁻ convolution not so bad, dig. convolution improving)

→ competition still open

→ improvements, active devices, integration

but what is at stake ?

THAT CONVOLUTION MACHINES ARE VERY USEFUL HAS STILL TO BE PROVEN

(3)

DIGITAL

O. logic : a side issue!

no significant gain expected (in "speed," space, energy)

other reasons may justify optical logic, but this is outside O.C.

O. memory : deserves watching

O. interconnects : major rationale for O.C.

- might some day justify O. logic + O. memo
- but – presently restricted to niches
  – integration wanting

(one illustration : O. for massively // cellular automa

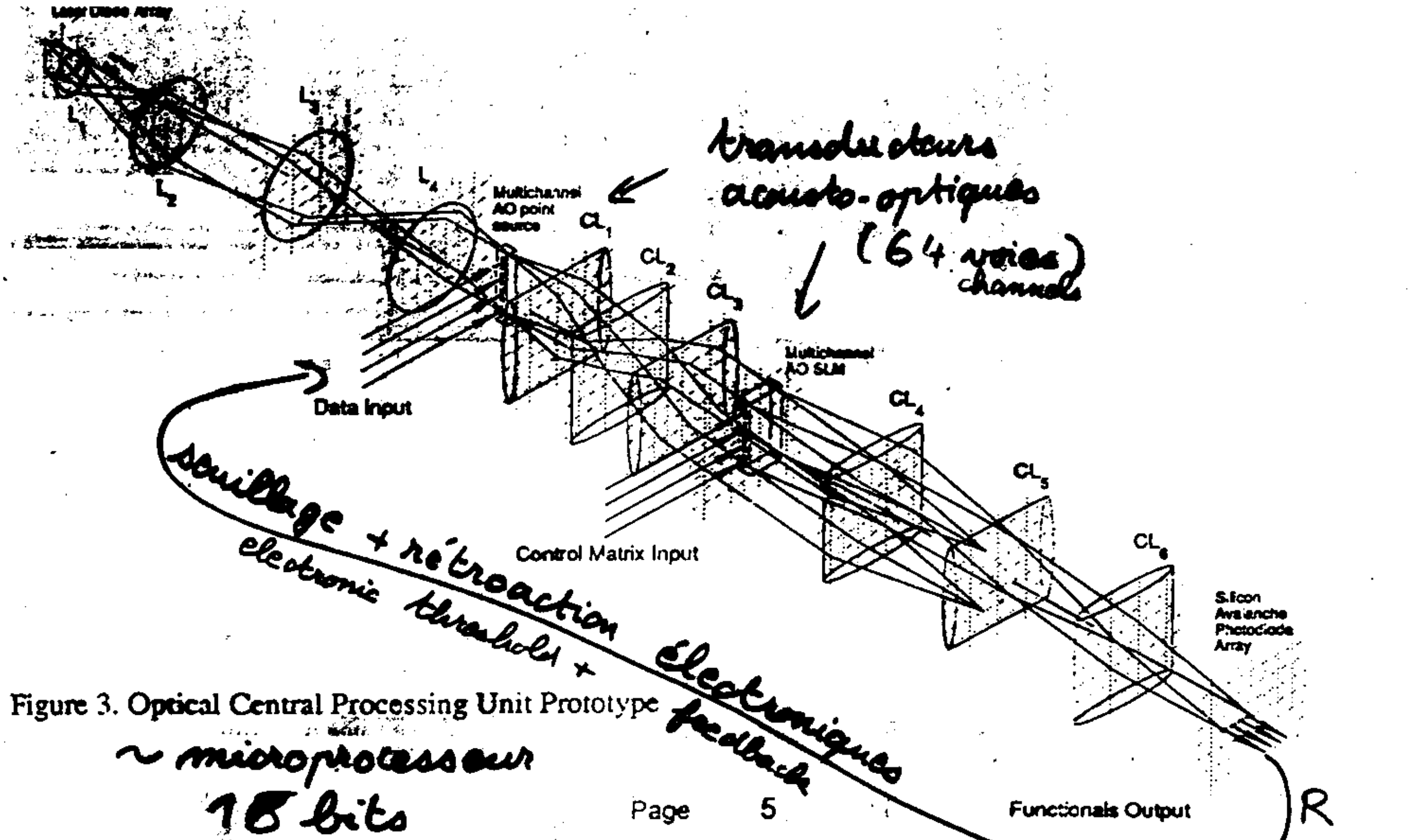


Figure 3. Optical Central Processing Unit Prototype

~ microprocesseur
16 bits
(émulation SUN SPARC 4/110)
100 MHz 1 fs/bit
10^{12} op. binaires / s

DOC II
P. Guilfoyle's 1989 - 1993

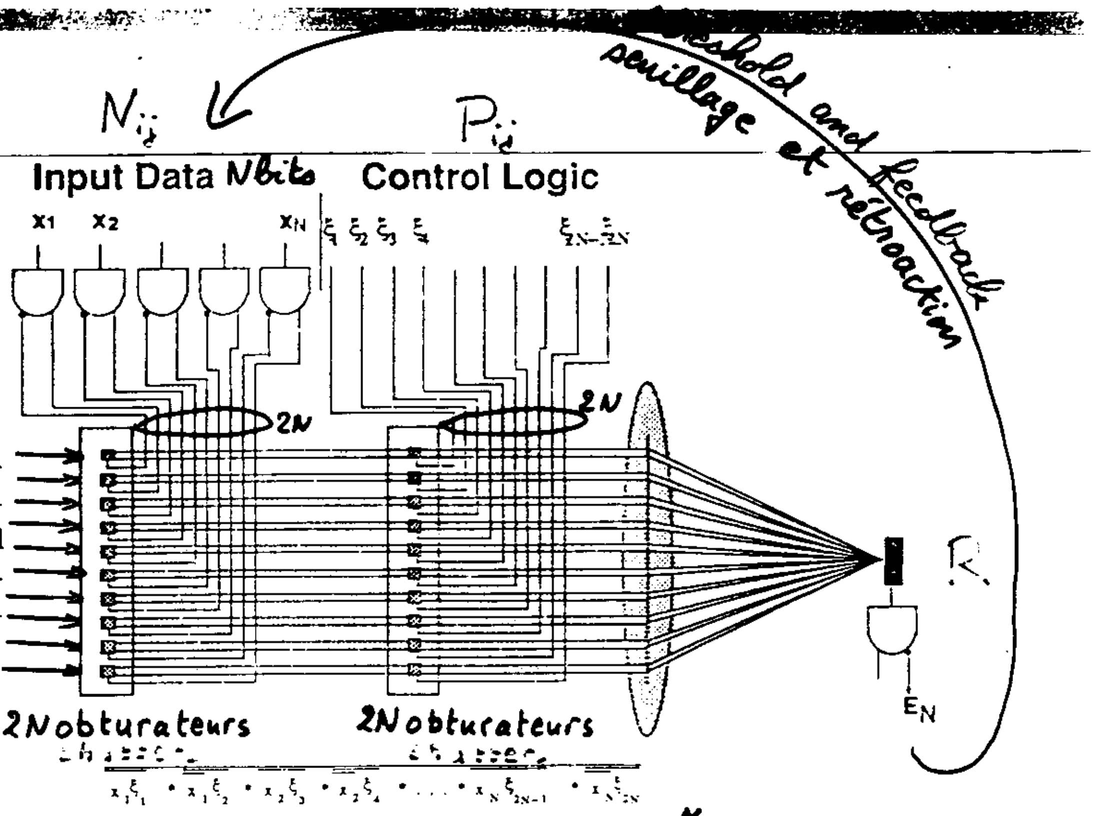
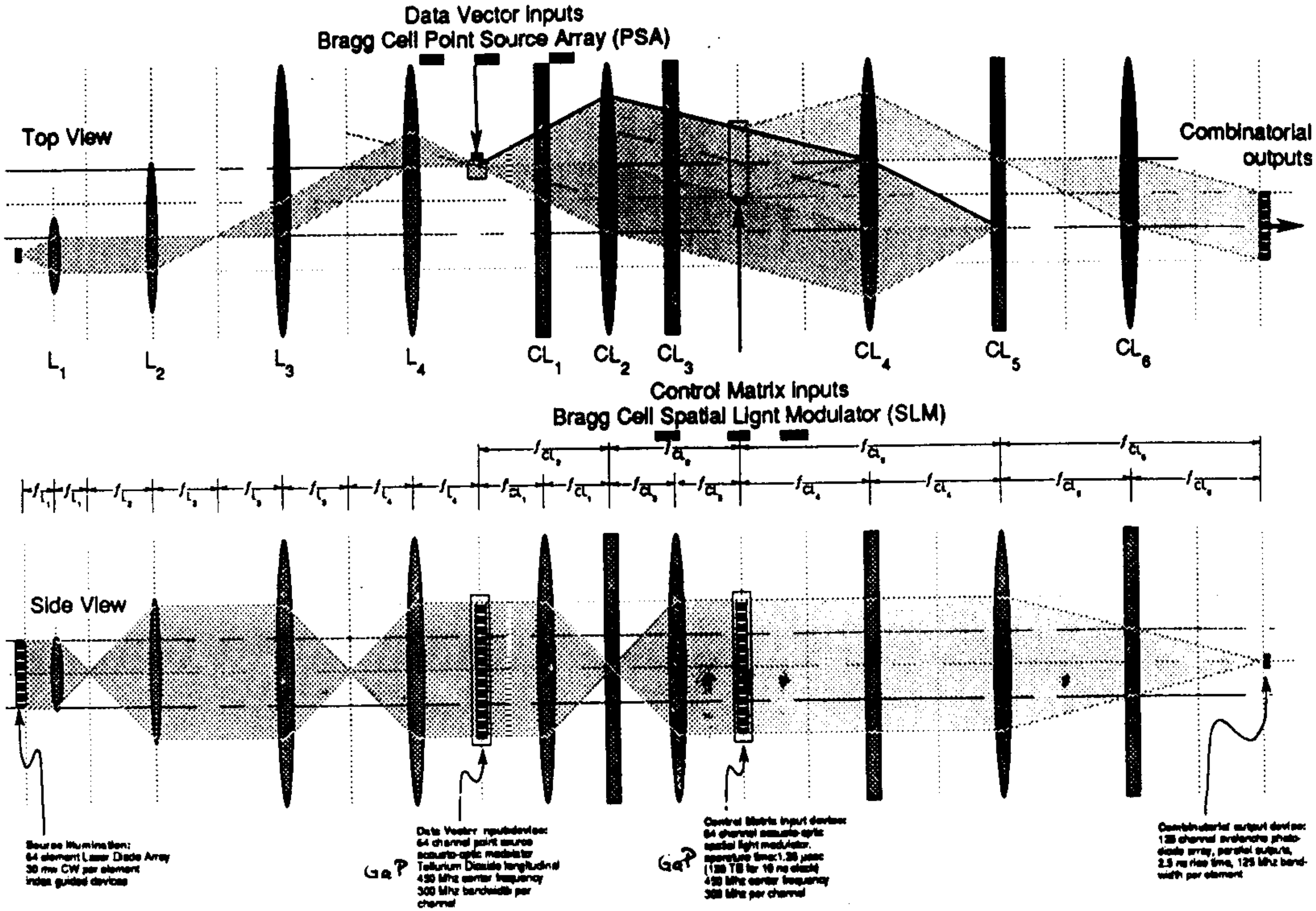


Figure 1: Simple optical computer implementation of Shannon's first set of equations used to perform arbitrary N-bit combinatorial dual rail multiplication or "AND"ing.

2 N faisceaux

une opération parmi 2^{2^N}

P. Guilfoyle 1989



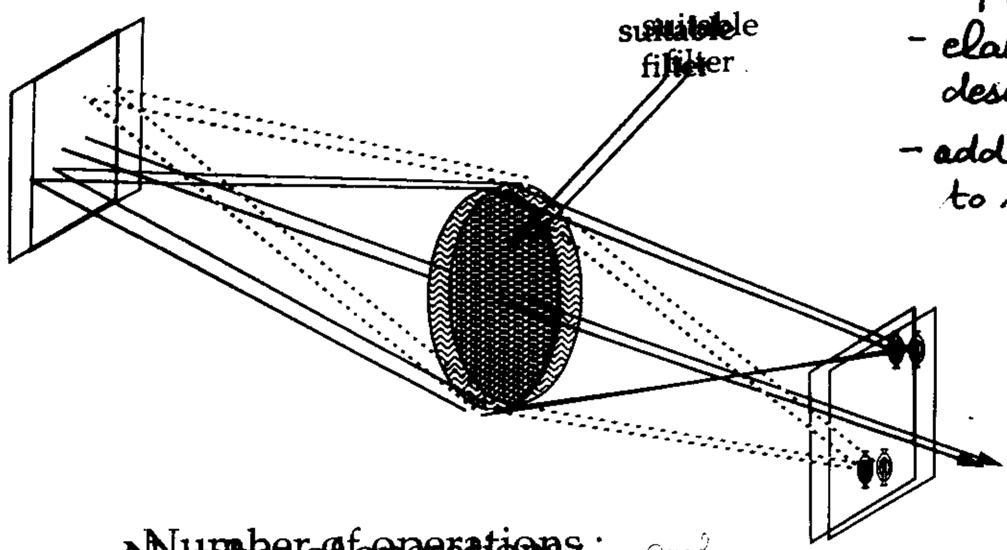
$$f_{CL_5} = 2f_{CL_6} = 2f_{CL_4} = 2f_{CL_2} = 4f_{CL_3} = 4f_{CL_1} = 4f_{L_4} = 4f_{L_3} = 4f_{L_2} = 8f_{L_1}$$

Figure 4: General Purpose Digital Optical Central Processing Unit Hardware Top and Side Views.

OPTICOMP 1990

(15)

Optical convolution/correlation



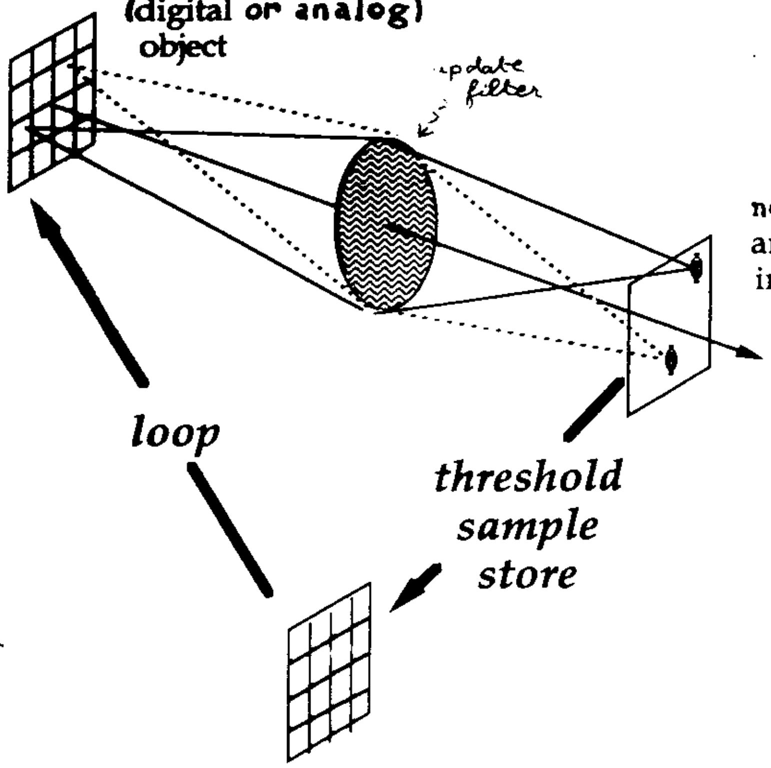
2 approaches
- elaborate filter design
- add something to setup

Number of operations :
$N_{pix} \times N_{psf}$

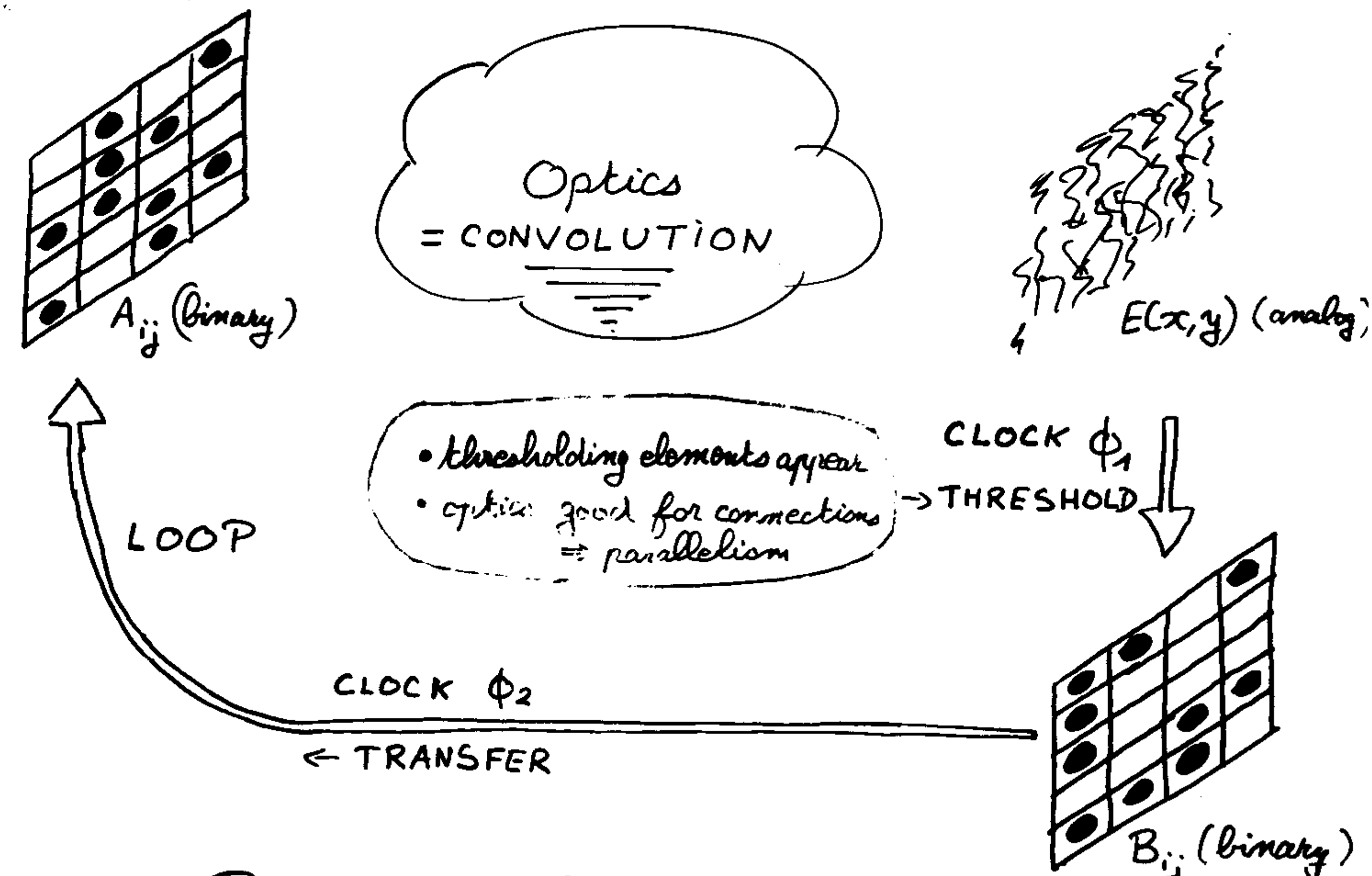
optical ... parallelism
analog
"optical scale" parallelism

Aug. 94

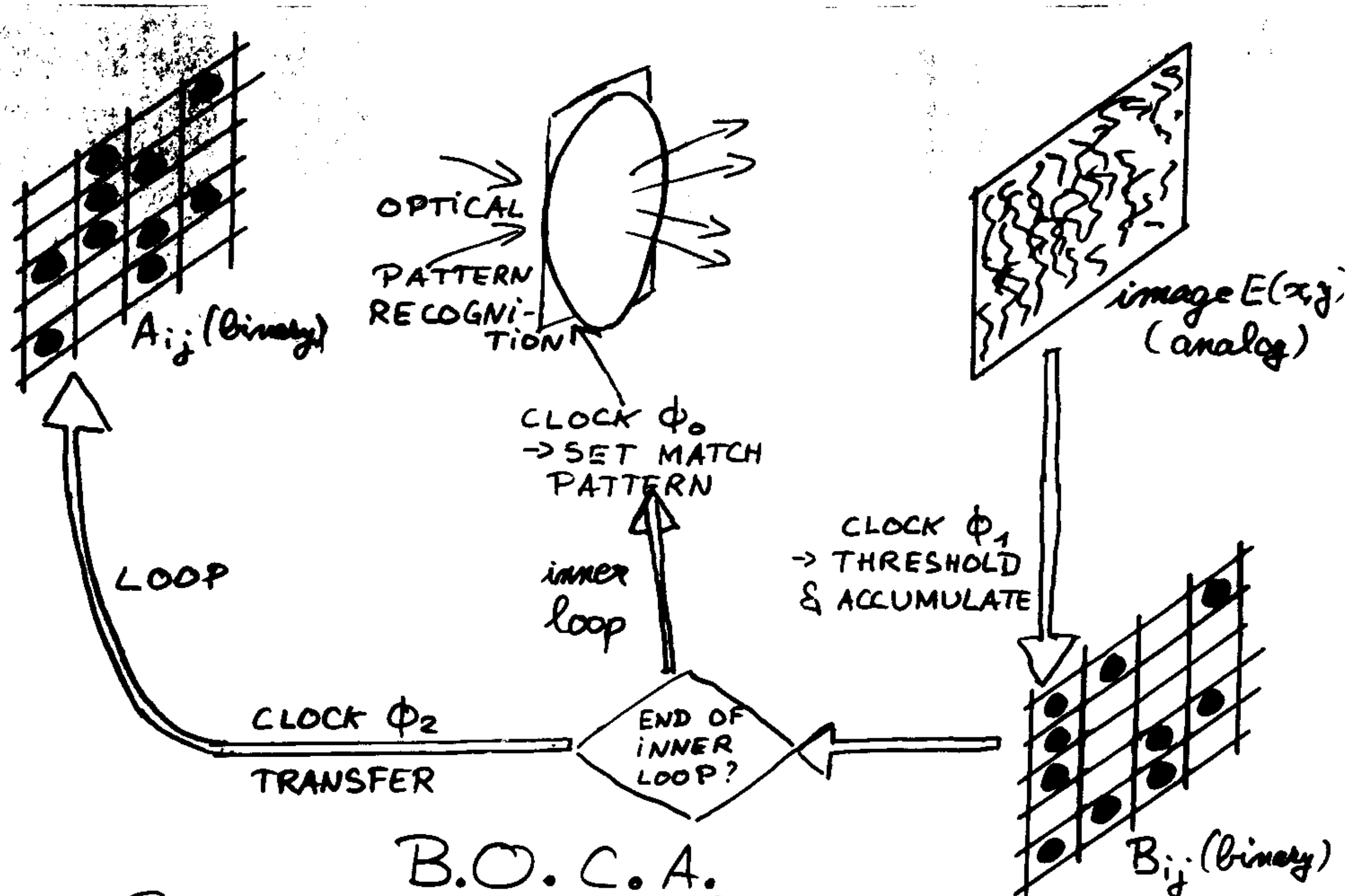
Optical cellular automaton



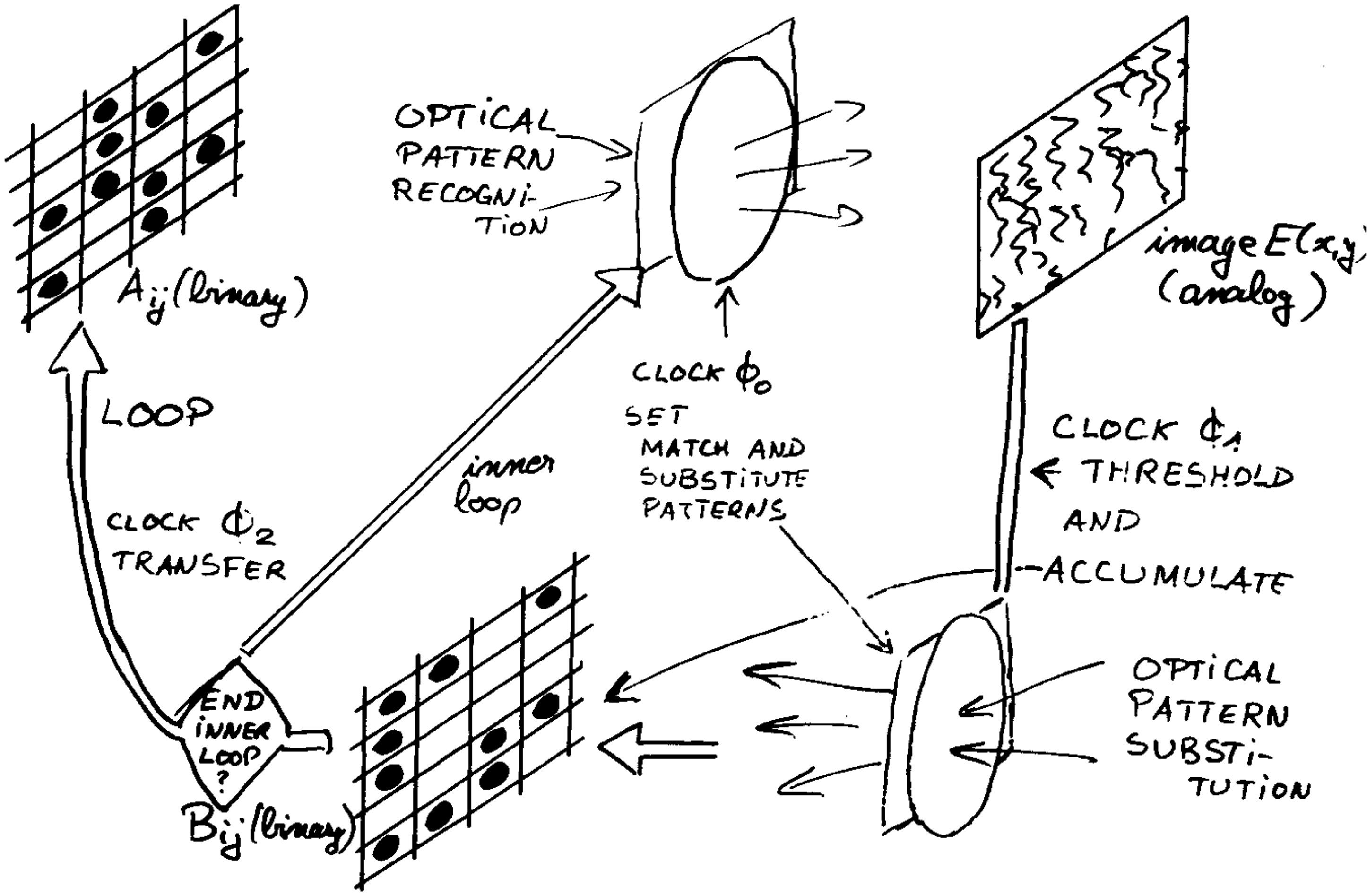
Aug. 94



Binary optical cellular processor



B.O.C.A.
Binary optical cellular automaton

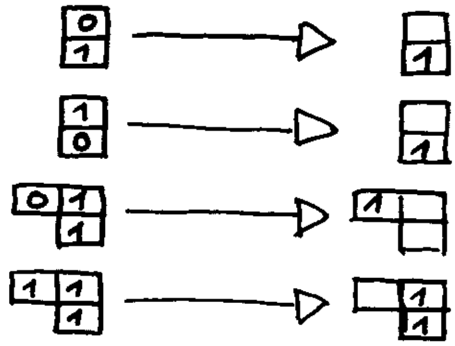


Optical symbolic substitution processor

INSTITUT D'OPTIQ

SYMBOLIC SUBSTITUTION RULES

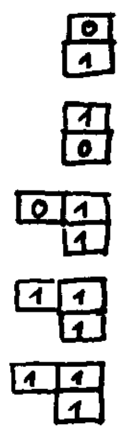
RECOGNIZE SUBSTITUTE



EXAMPLE: BINARY ADDITION

B.O.C.A. MATCH PATTERN

RECOGNIZE



Symbolic substitution and BOCA
- suggest different architectures
- but are logically equivalent.

INSTITUT D'OPTIQ
JUILLET 90

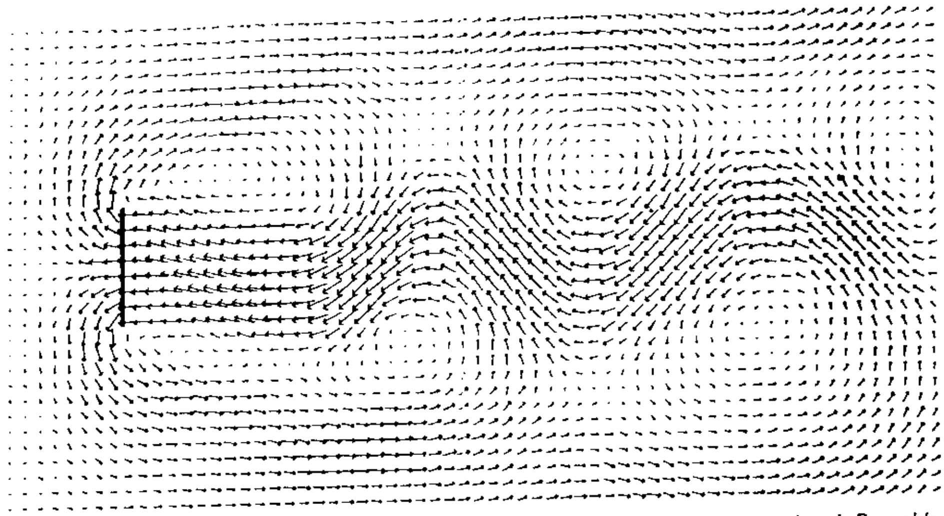
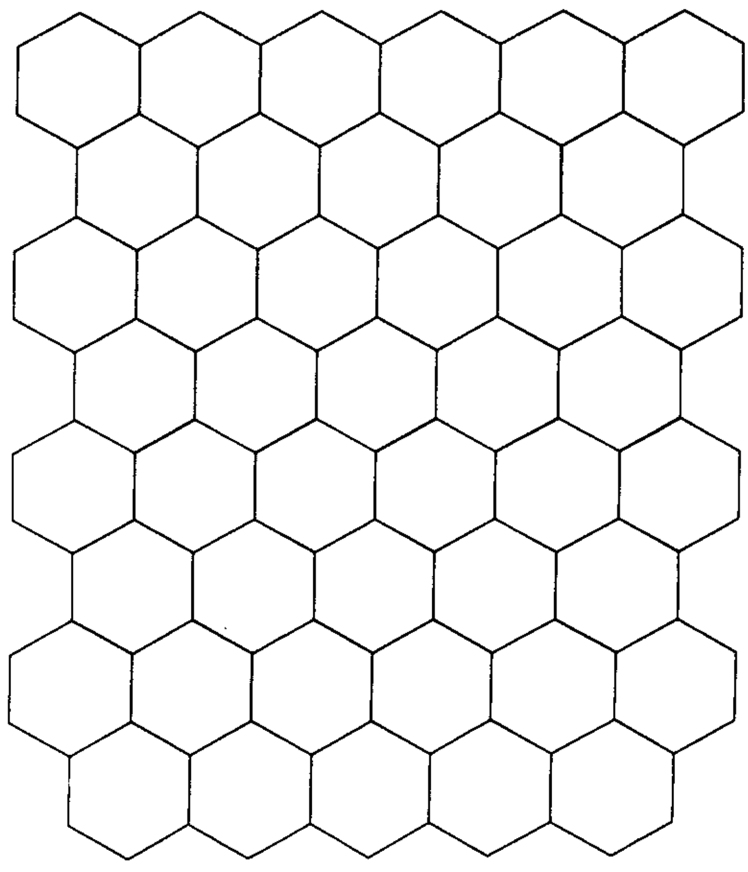
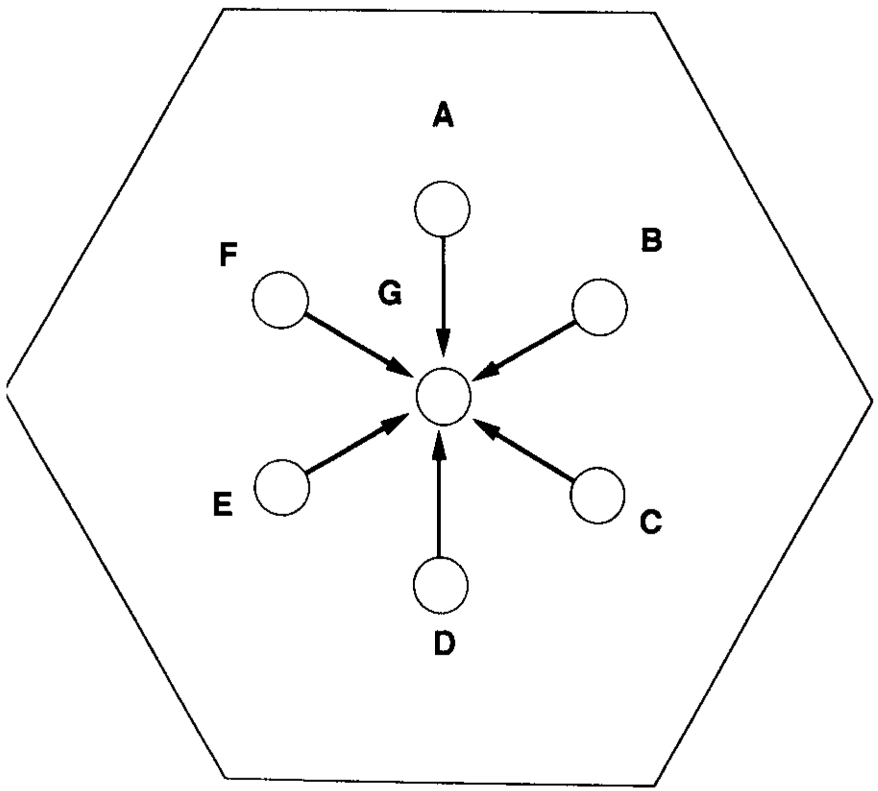


Fig. 2. Écoulement autour d'une plaque mince en mouvement dans le gaz pour un nombre de Reynolds de l'ordre de 90. Les flèches représentent la direction et le module du flux aux nœuds d'un maillage 32 × 64.

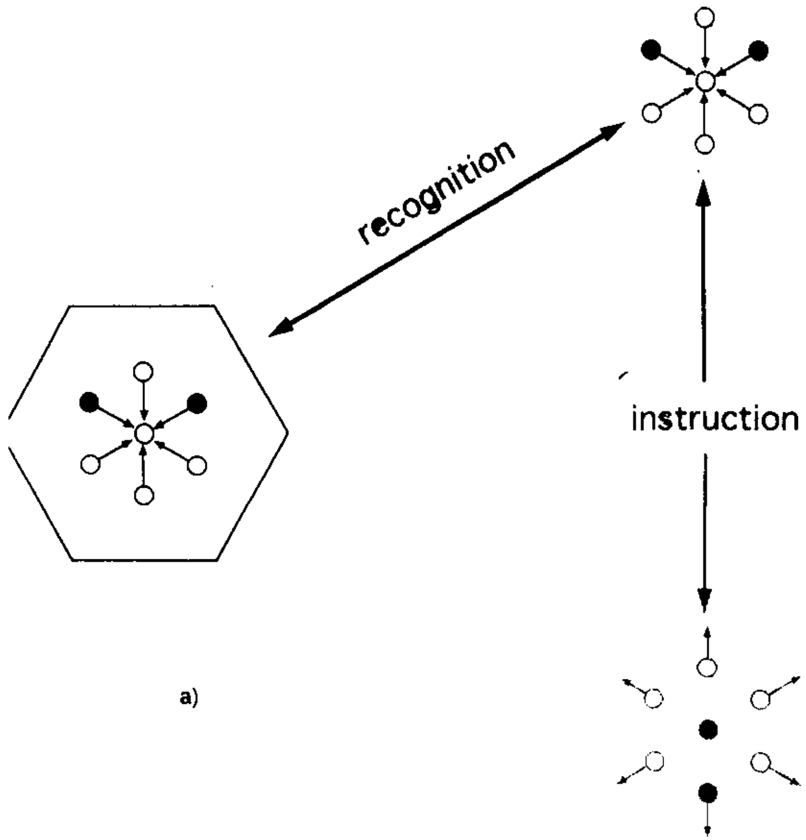
D. d'HUMIERES
P. LALLEMAND
Y. POMEAU

Bull de la SFP n°25 p14-15 (1986)

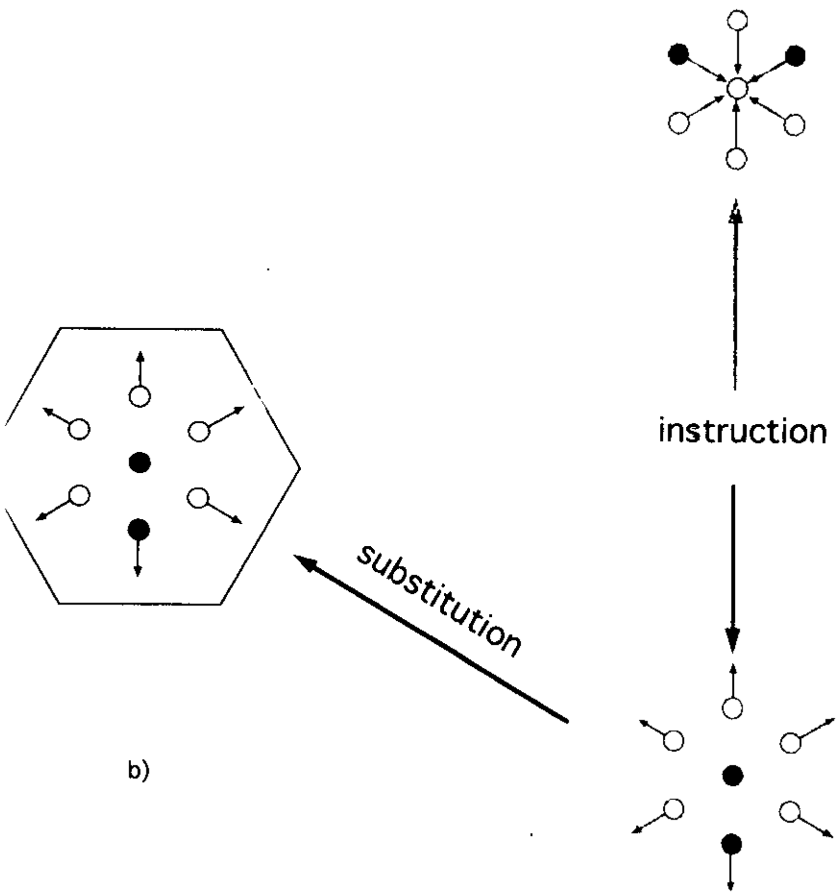




One PE : a seven-bit machine



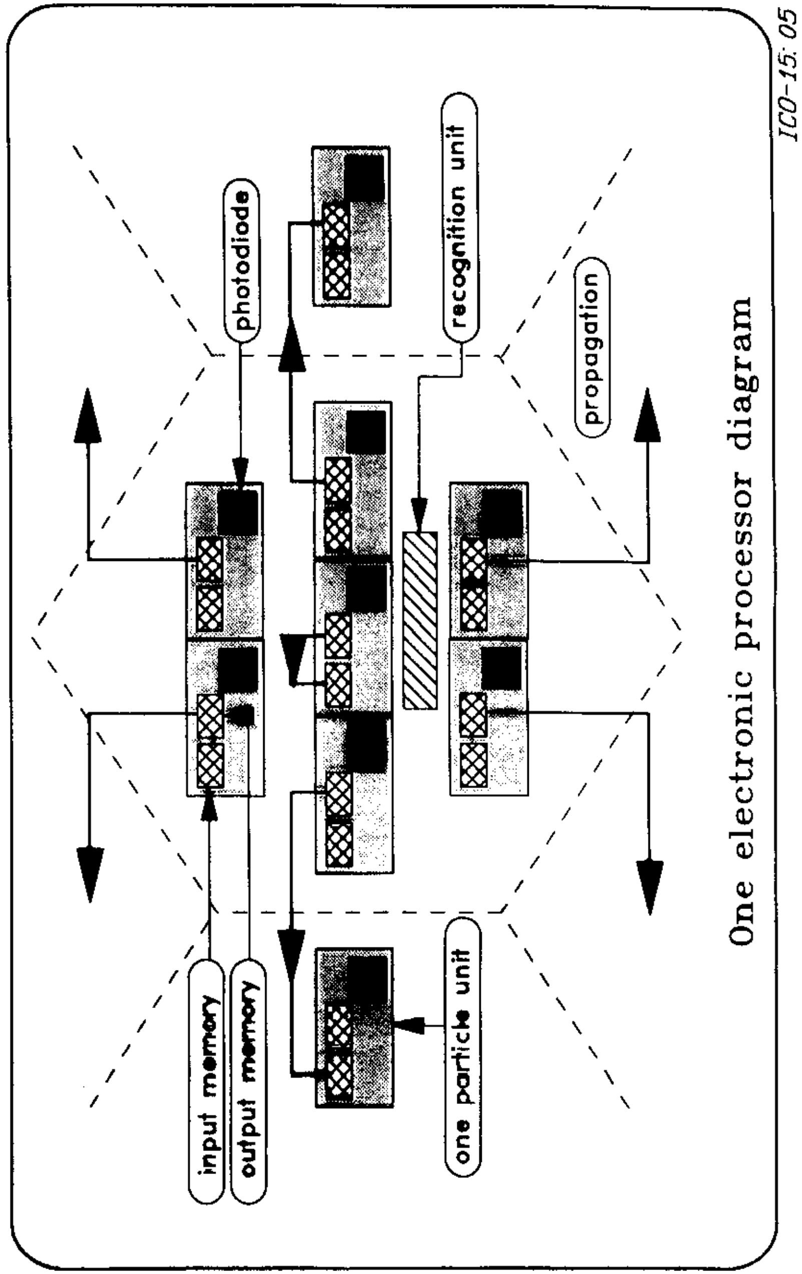
Clock cycle 1



b)

Clock cycle 2

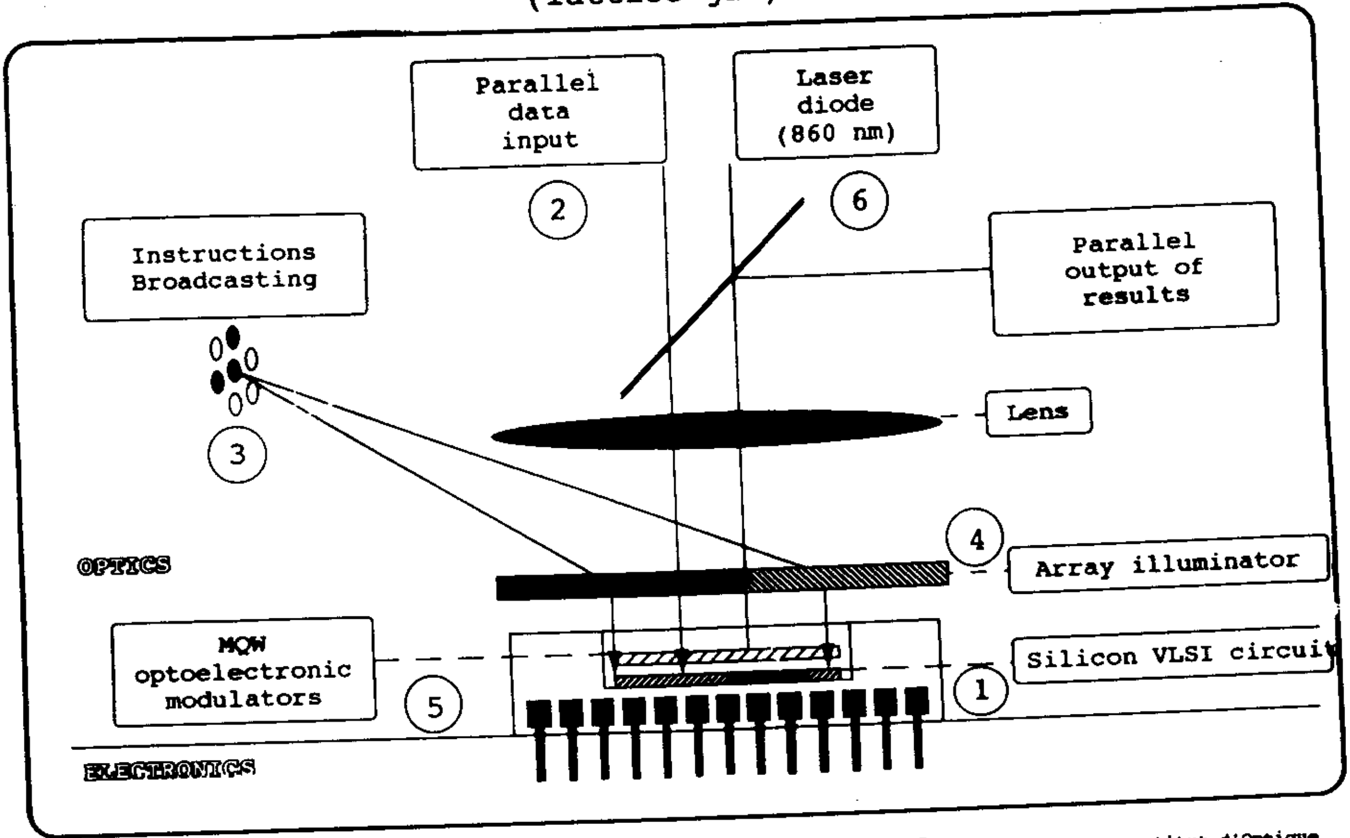
ELECTRONIC CIRCUIT



One electronic processor diagram

ICO-15: 05

Opto-Electronic Cellular ...
(lattice gas)



All non-nearest neighbor connections done optically
about 3000 optical I/O per cm^2

Institut d'Optique
Thomson CSF LCR
Institut d'Electronique Fondamentale
1990-1992

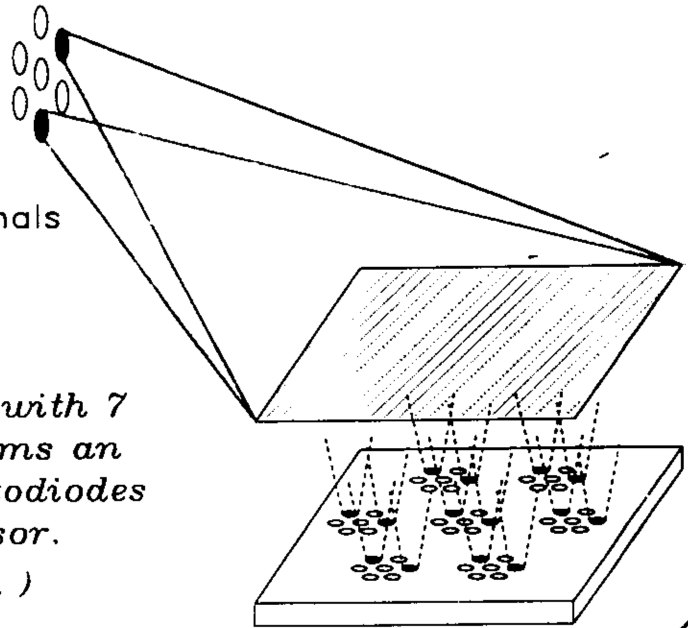
(22)

ARRAY ILLUMINATOR HOLOGRAM

TO BROADCAST THE OPTICAL SIGNALS TO THE PHOTODIODE ARRAY ON THE ELECTRONIC CIRCUIT.

REQUIREMENTS :

a) Focus light onto pixels
b) High efficiency
c) Transparent for other signals
d) Short focal distance



The hologram illuminated with 7 sources (laser diodes) forms an image of them on the photodiodes of each elementary processor.

(Microlens hologram)

INSTITUT D'OPTIQUE
1990

OPTOELECTRONIC CELLULAR AUTOMATA

CRITICAL EVALUATION OF THE ROLE OF OPTICS

Examine {input, output and instruction broadcasting} performance with respect to:

- energy on chip
- area on chip
- interconnect layers (CMOS)
- fault tolerance

Assumptions:

$1\ cm^2$ of Si = one chip with

$K \times K = 100 \times 100$ PE's, all $100 \times 100\ \mu m^2$

VLSI : CMOS $\lesssim 1\ \mu m$ (at present, $1000/cm^2$ realistic)

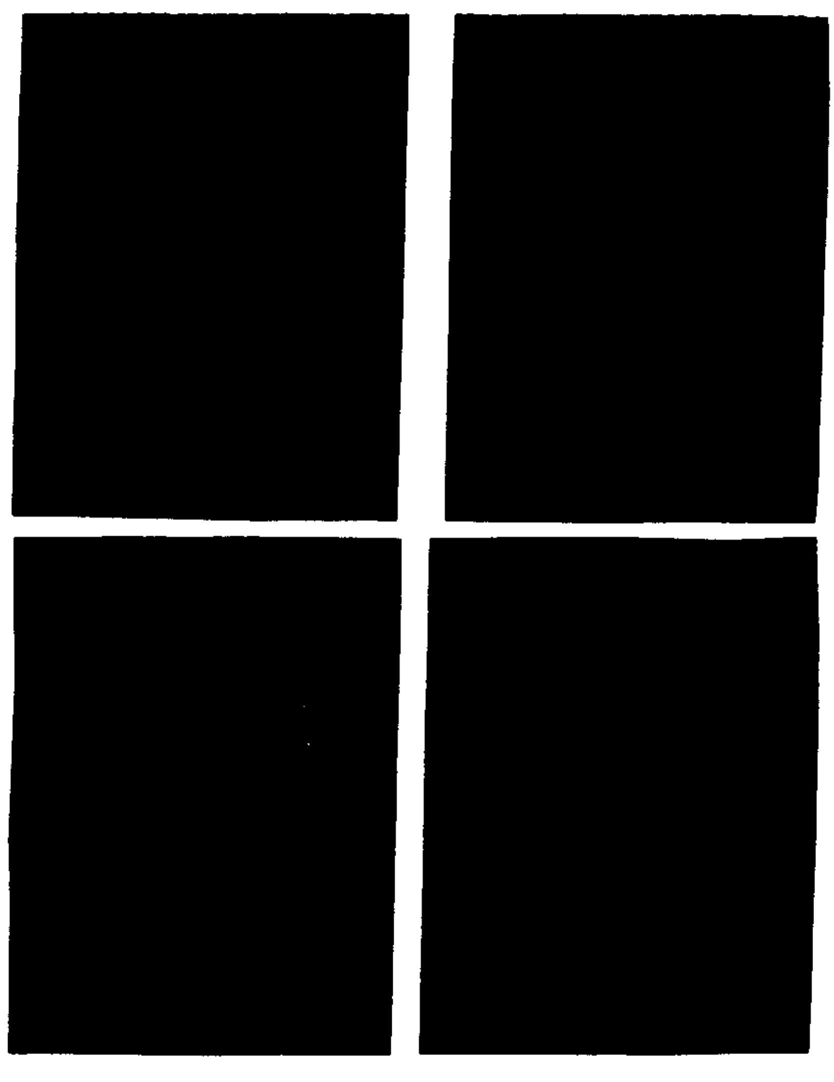
CONCLUSIONS:

- parallel input using optics : important if many inputs needed
- parallel output using optics : id.
  difficulty: flip chip bonding
- parallel instruction broadcasting:
  - optics does not appear as a drawback in any respect *
  - in area, interc. layers, reliability: real advantage, increasing with N (but not orders of magnitude)

  * assuming progress in O-E integration (compactness, self-alignement)
- cell. automata: good test case

Image processing as an optimisation problem

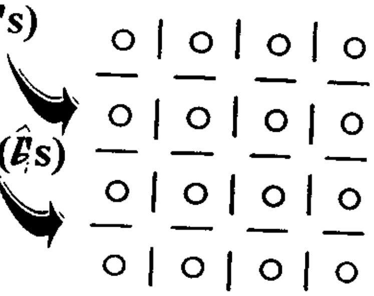
- Define energy function $E(\hat{\underline{x}}, \underline{x})$
  - $\hat{\underline{x}}$: estimate (sampled)
  - $\underline{x}$: input data (sampled)
- Minimize E, given $\underline{x}$, with respect to $\hat{\underline{x}}$

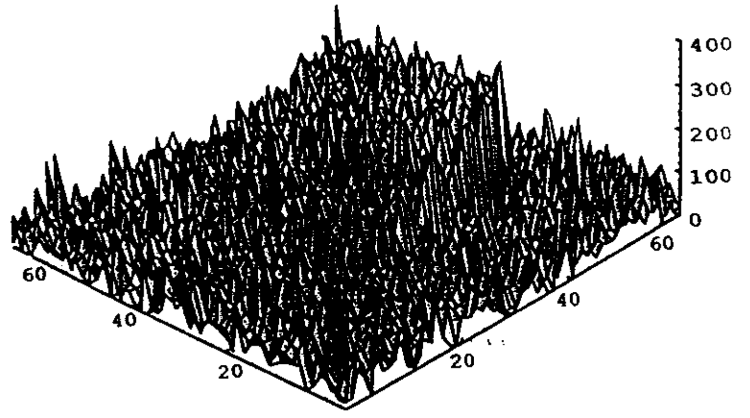


Geman 1990.

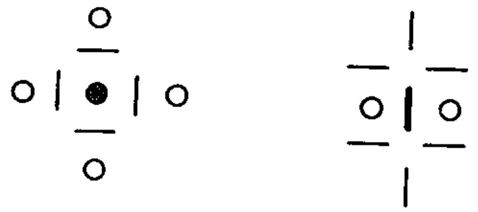
Intensity site (x_i's)

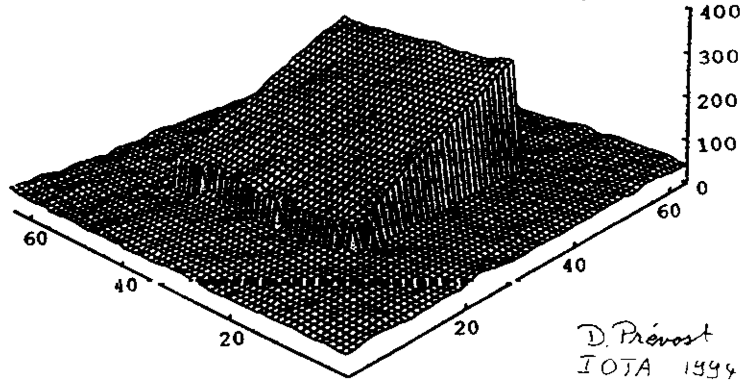
Binary line site ($\hat{b}_i$s)





Nearest-neighbor interaction:





D. Prévost
IOTA 1994

(25) ⊗ <u>One reasonably simple problem</u>:

<u>noisy image restoration preserving borders</u>

Discuss <u>1-D</u> version: "the weak string problem"

Data structure:

... | x_i | x_{i+1} | ...

estimate → ... $\hat{x}_i$ $\hat{b}_i$ $\hat{x}_{i+1}$ $\hat{b}_{i+1}$ ...

$\hat{x}_i$ ↙ grey levels

$\hat{b}_i$ ↓ border, binary: $\begin{cases} 1 & \text{if border present} \\ 0 & \text{if not} \end{cases}$

Energy function:

$$E(\underline{\hat{x}}, \underline{\hat{b}}, \underline{x}) = \sum_{i=1}^{N_{pix}} (\hat{x}_i - x_i)^2 + \lambda^2 (\hat{x}_i - \hat{x}_{i+1})^2 \cdot (1 - \hat{b}_i) + \beta^2 \hat{b}_i$$

($\underline{\hat{x}}$, $\underline{\hat{b}}$: to be estimated; $\underline{x}$: data)

Problem complexity

1) "Good" E functions will usually require exhaustive search of $\hat{\underline{x}}, \hat{\underline{b}}, \ldots$ space:
number of operations $\sim$ $\boxed{\alpha_1^{N_{pix}}}$: hopeless

2) Heuristic methods needed.
Example: simulated annealing, a stochastic algo.

typically $\boxed{\alpha_2 \cdot N_{pix}}$ operations

$10^7 \times 10^6? \times 25/\text{second}?$ still VERY large.
$10^4?$

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Optics for optical scale parallelism

1) $\delta E_i = (\hat{\underline{x}} * PSF)_i$

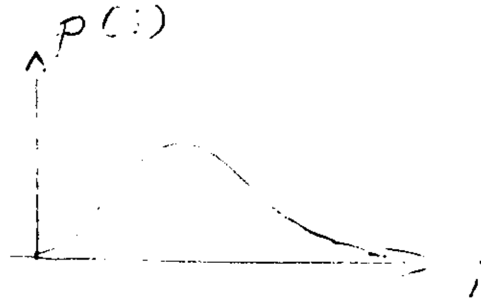
δE is a convolution in many cases
quadratic terms in $\hat{\underline{x}}$ or $\underline{x}$
$\hat{b}$ in ... string

Optics useful is PSF larger than nearest neighbours

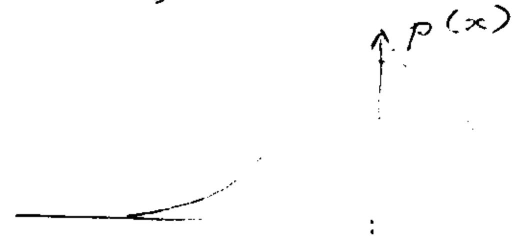
2) Optics to provide the random numbers

typically N_{pix} independent random numbers at $\gtrsim$ MHz rate

- use speckle

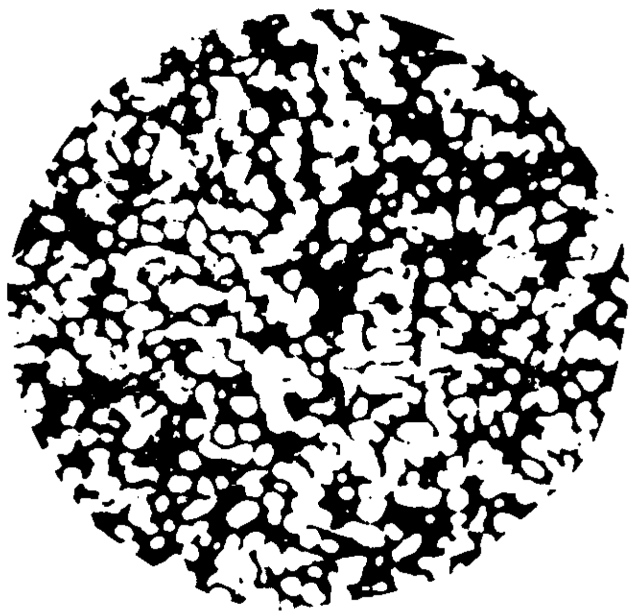


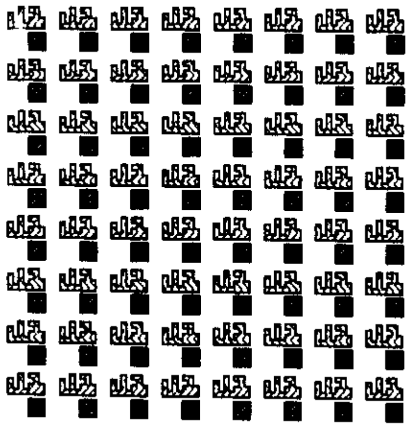
- use the difference between two adjacent speckle samples



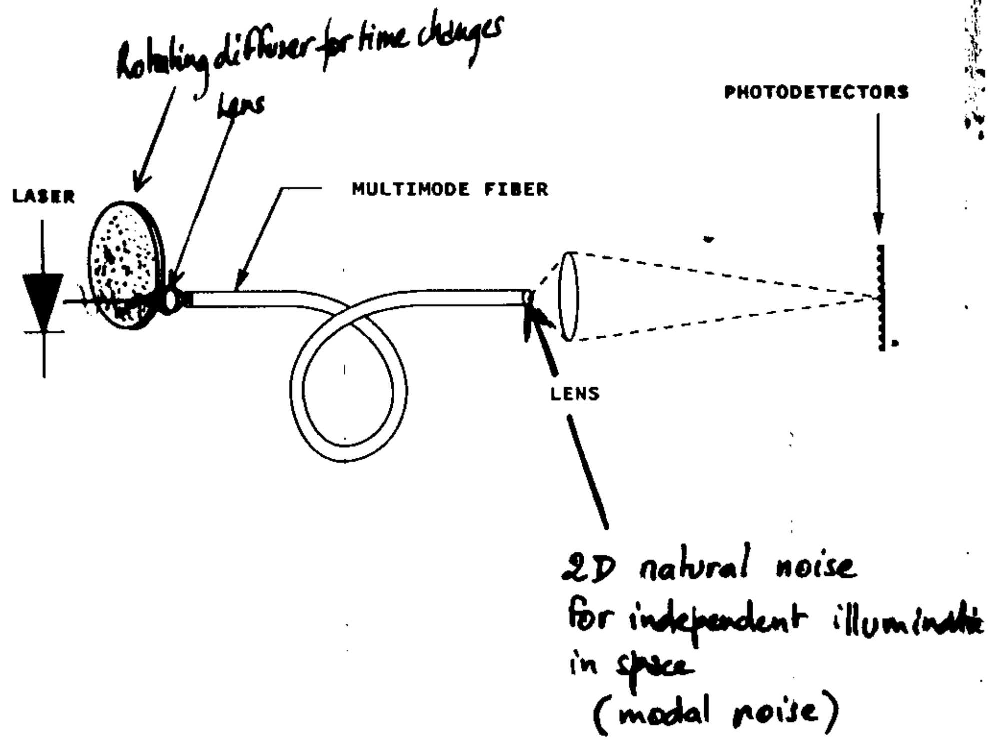
close to $\frac{1}{\cosh^2 x}$

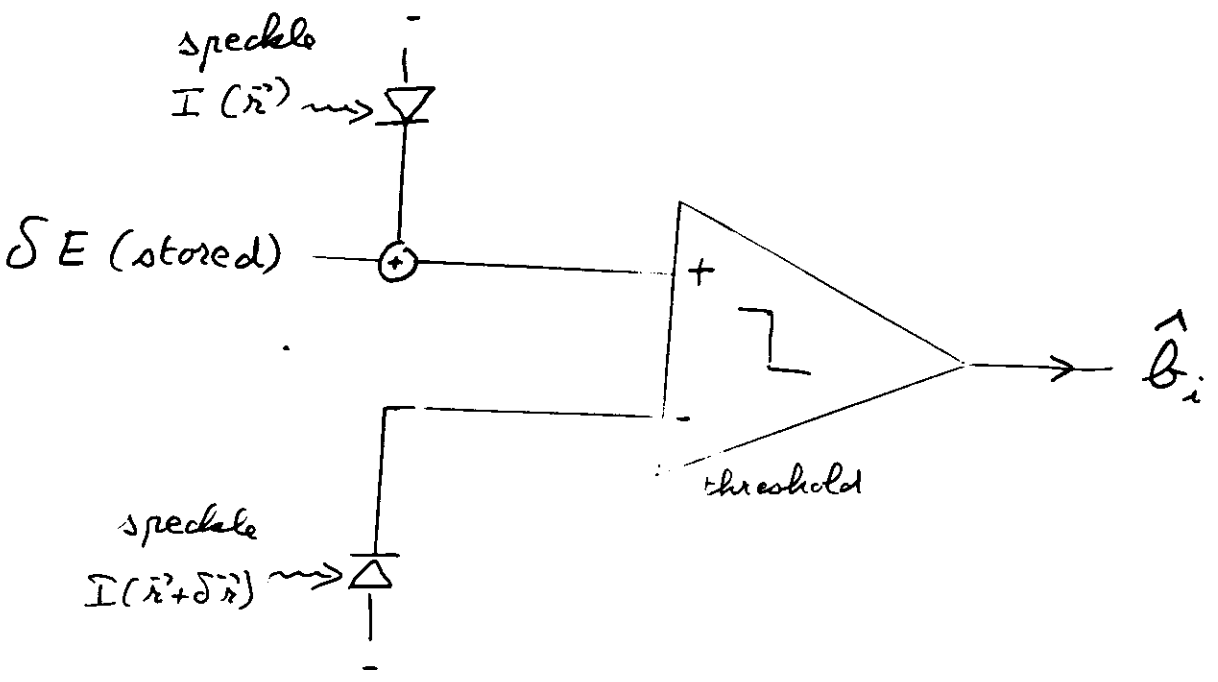
$\Rightarrow x = i(\vec{r}) - i(\vec{r}+\delta\vec{r})$





OPTICAL SETUP





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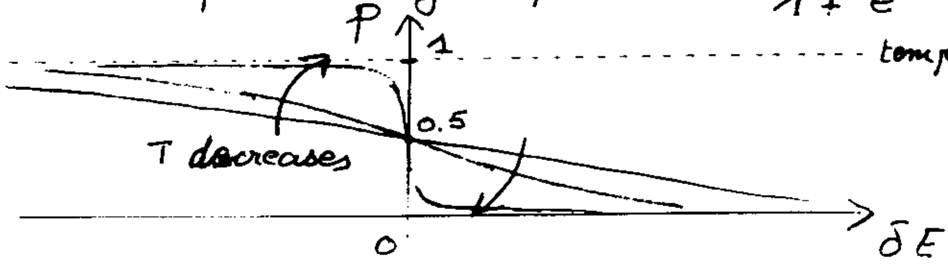
Simulated annealing
for the $\hat{\underline{b}}$ pixels of a "weak string"

uter
oop

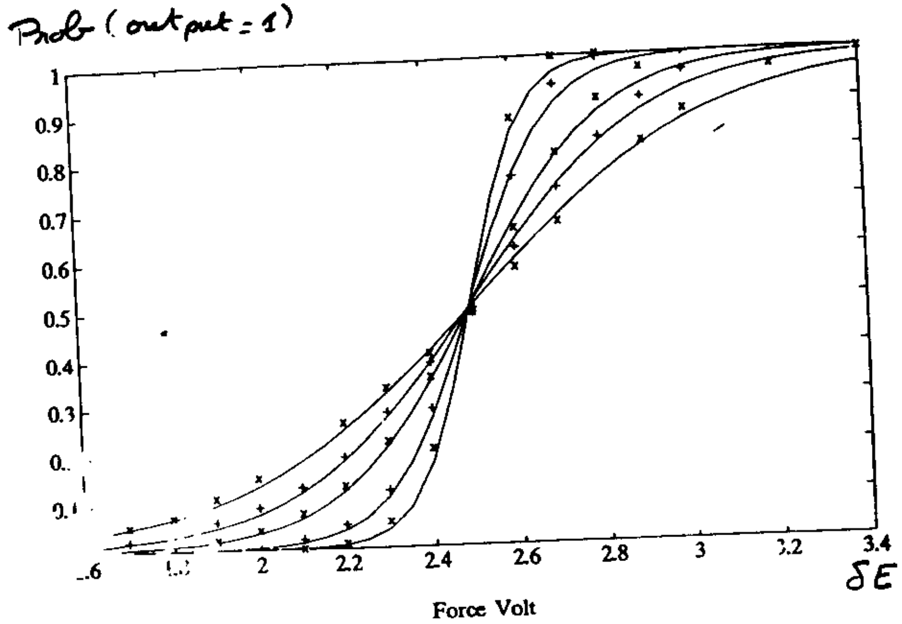
inner loop
↑ in parallel

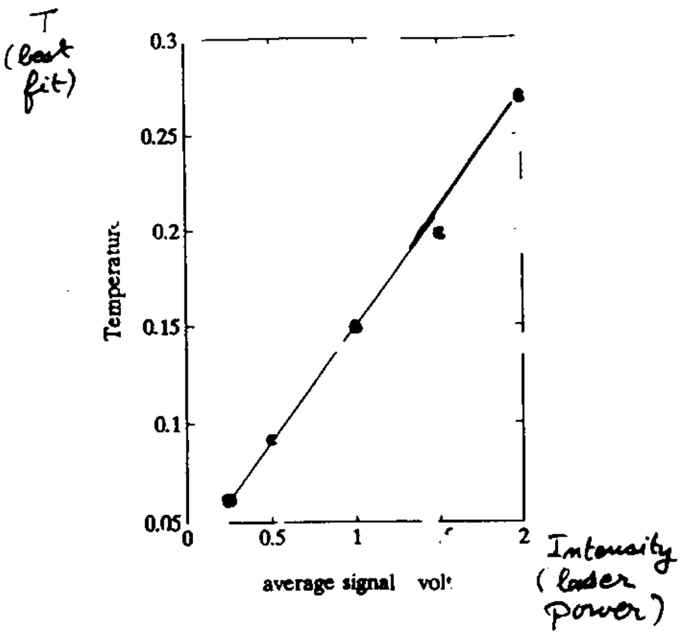
- select one pixel i
- compute $\delta E = E(\ldots, \hat{b}_i = 1, \ldots) - E(\ldots, \hat{b}_i = 0, \ldots)$
- accept $b_i = 1$ with probability $p(\delta E) = \dfrac{1}{1 + e^{\delta E / T}}$ ← temperature

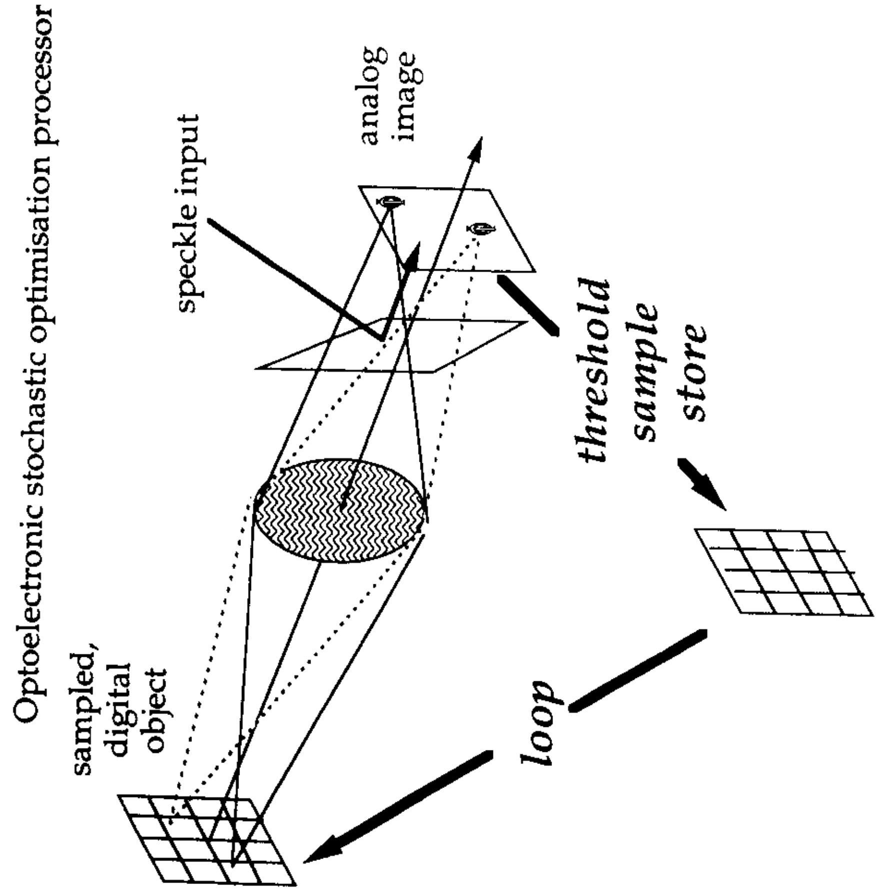


slowly d[illegible] T ("annealing")

experimental results







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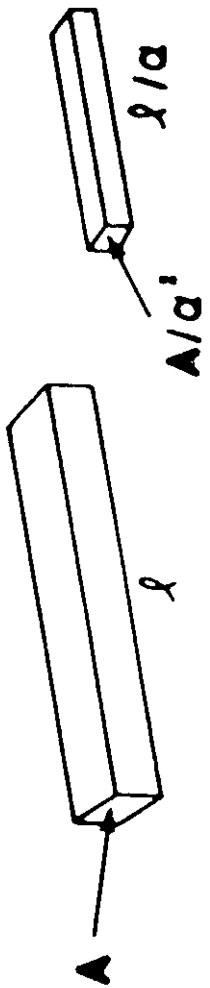
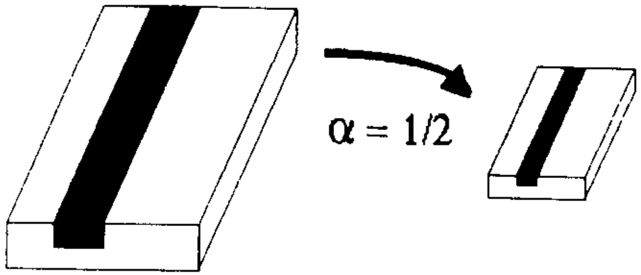


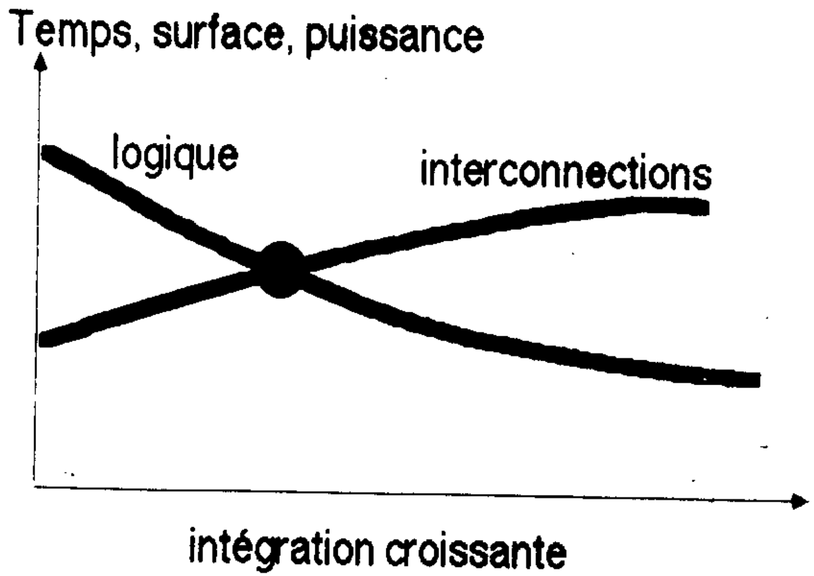
CAPACITANCE	C	C/α
RESISTANCE	R	Rα
TIME CONSTANT	RC	RC

Figure 1 Scale independent *RC* time constant.

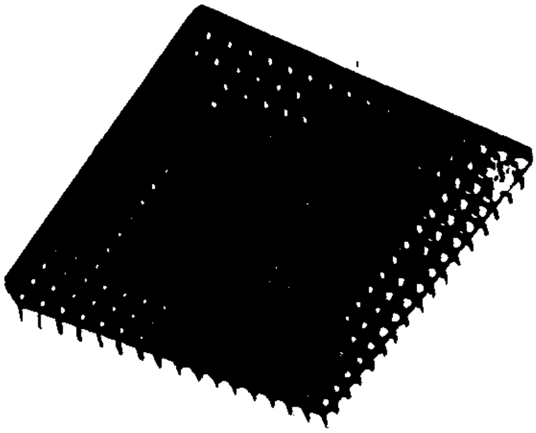
Besoins en interconnexions des processeurs (approximations d'un opticien)

- exemple : les puces
  - lois d'échelle : les interconnexions prennent une part croissante du temps, de la surface, de la puissance





80860 Intel



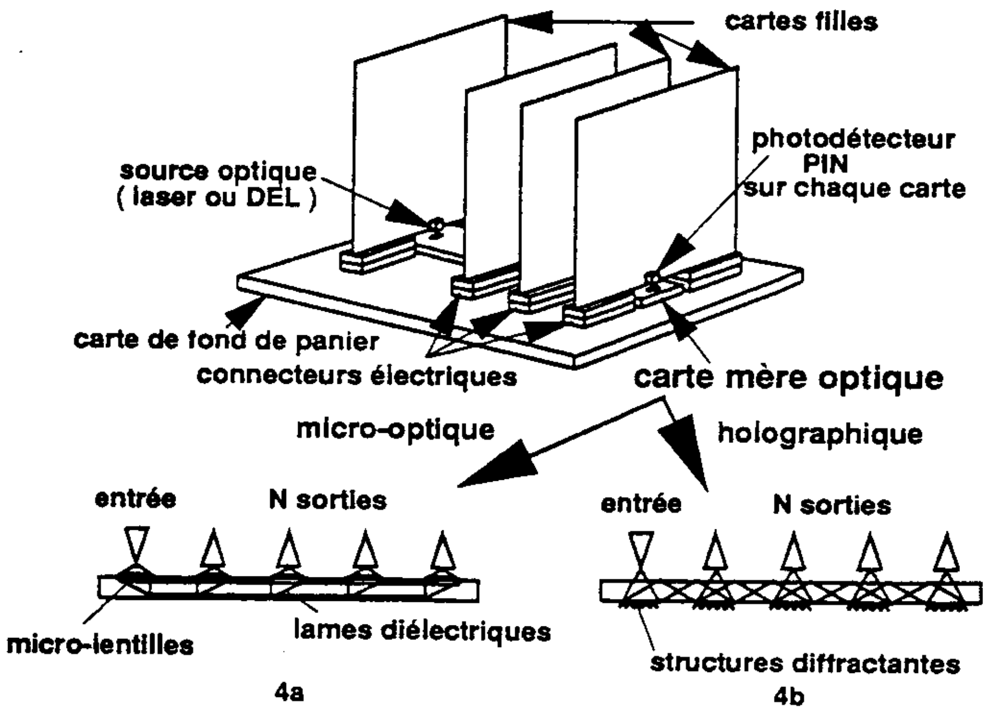
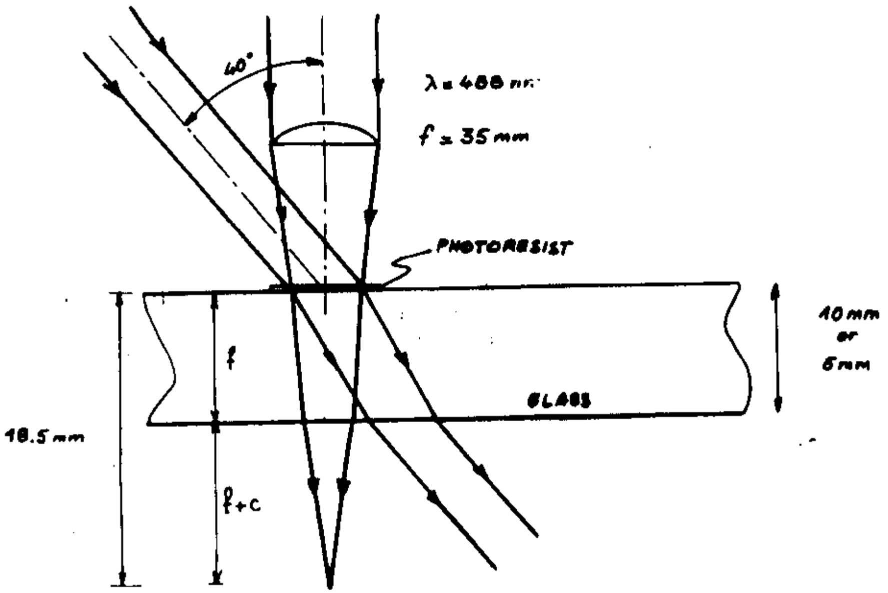


Figure 3 :

Figure schématique représentant un exemple d'interconnexion entre plusieurs cartes utilisant une carte mère optique de fond de panier.

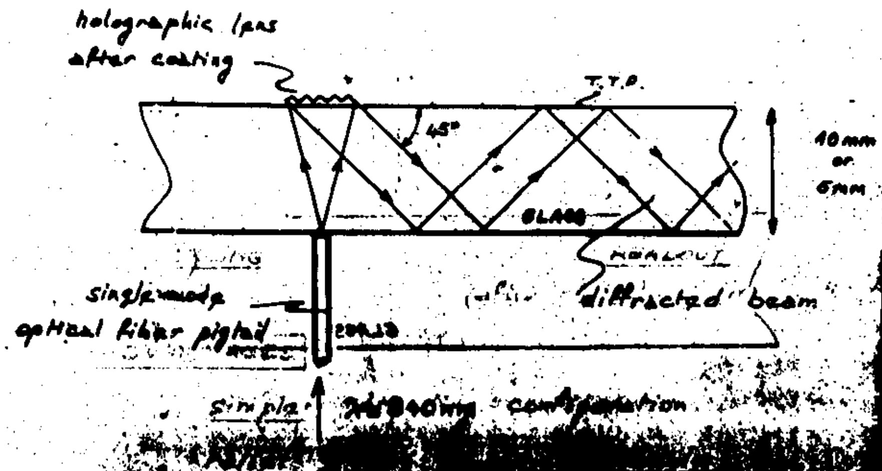
a) carte mère optique utilisant des composants optiques conventionnels (microlentilles, couches diélectriques, miroirs).

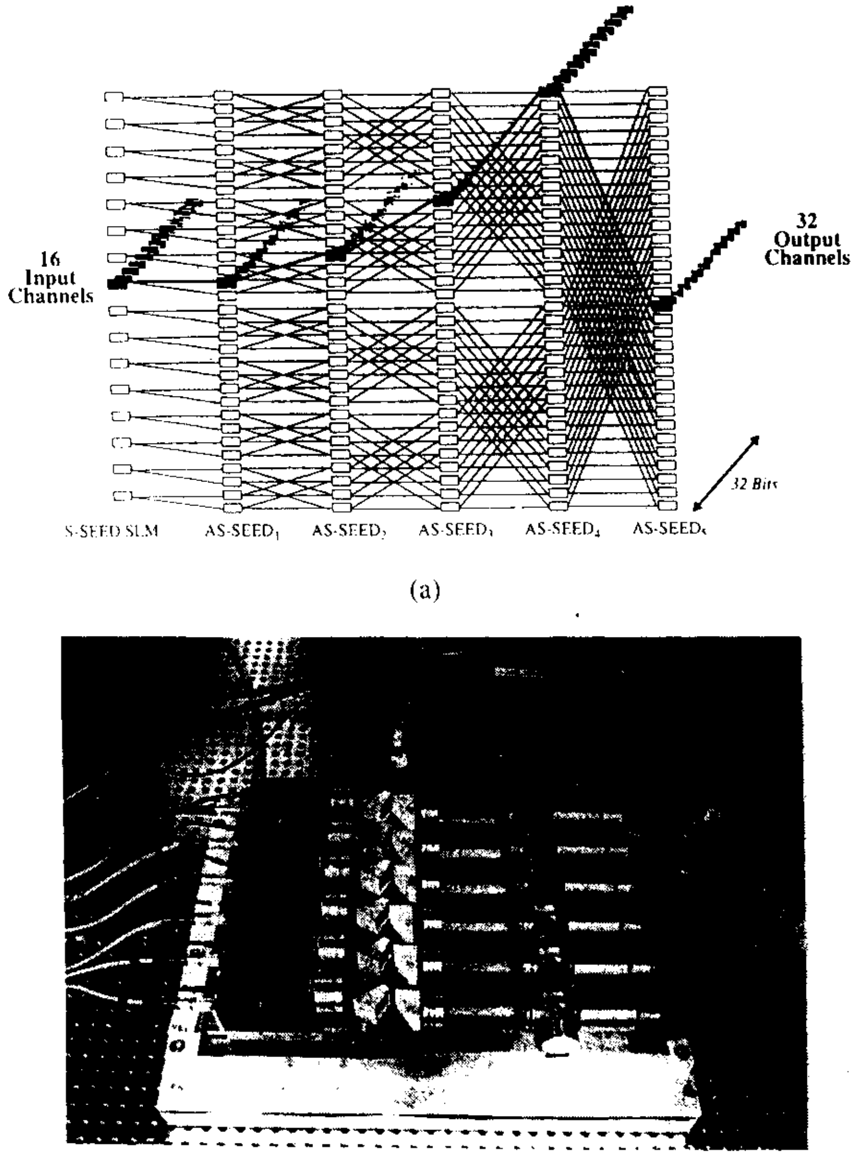
b) carte mère optique utilisant des composants holographiques fonctionnant "hors-d'axe".



B7 **RECORDING**

B8 **READOUT**

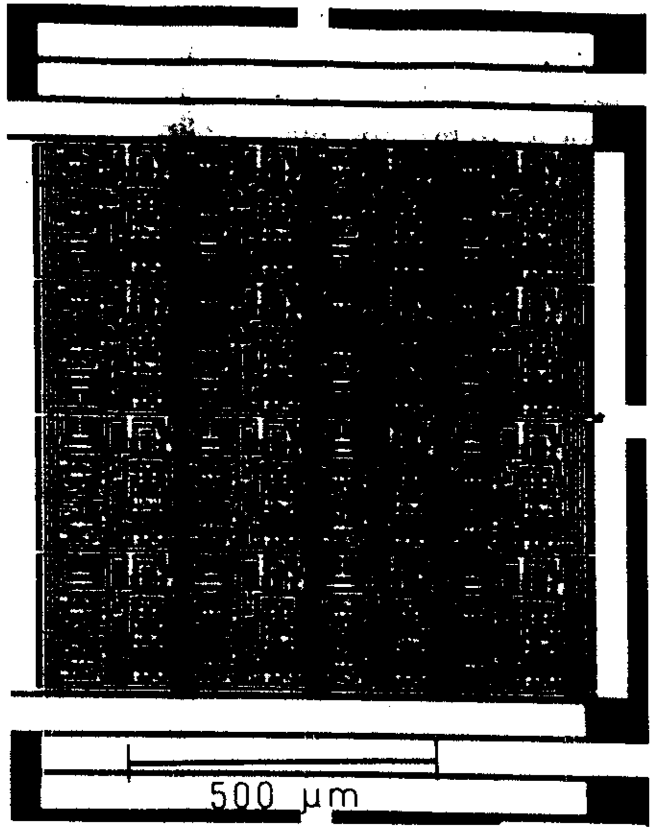




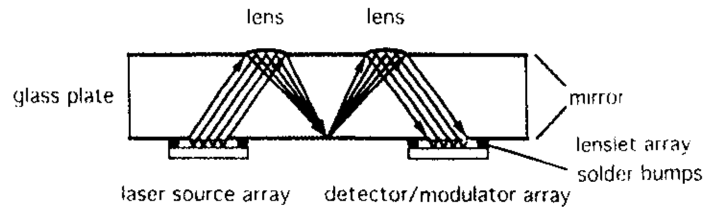
(a)

(b)

Fig. 18. *System*4. (a) Network topology. (b) Picture of demonstrator.

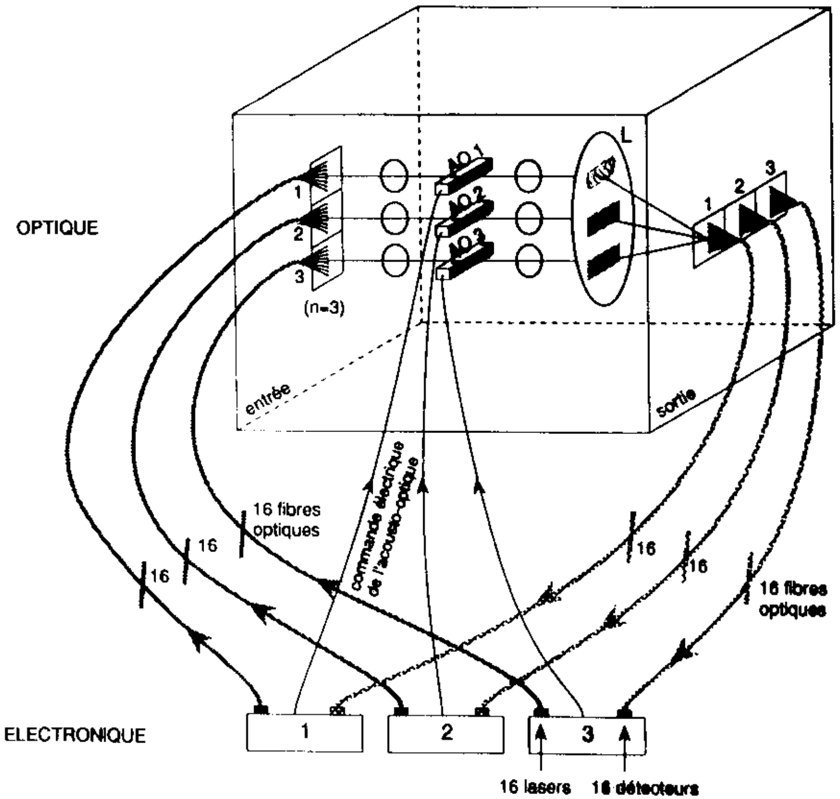


4 × 4 smart-pixel array in FET-SEED technology (courtesy T. Woodward, AT&T Bell Laboratories).



Parallel planar optical interconnections using micro-optical elements and optoelectronic chips integrated onto the substrate.

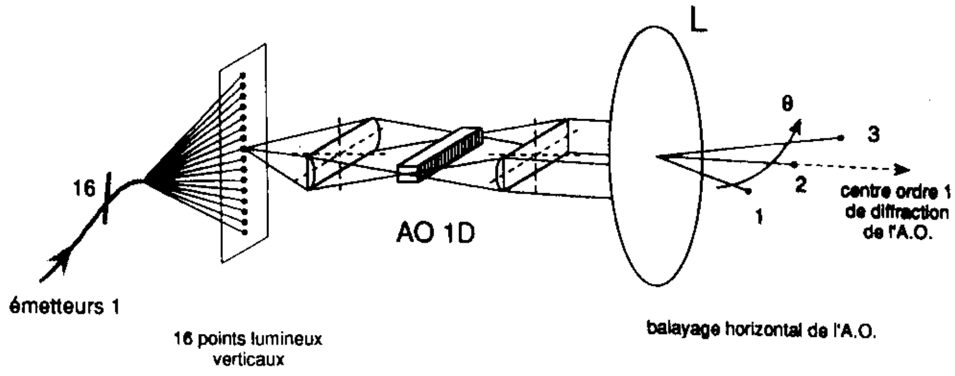
CUBE D'INTERCONNEXION OPTIQUE



n= 3 : nombre d'unités électroniques à interconnecter

b=16 : nombre de bits à transmettre en parallèle

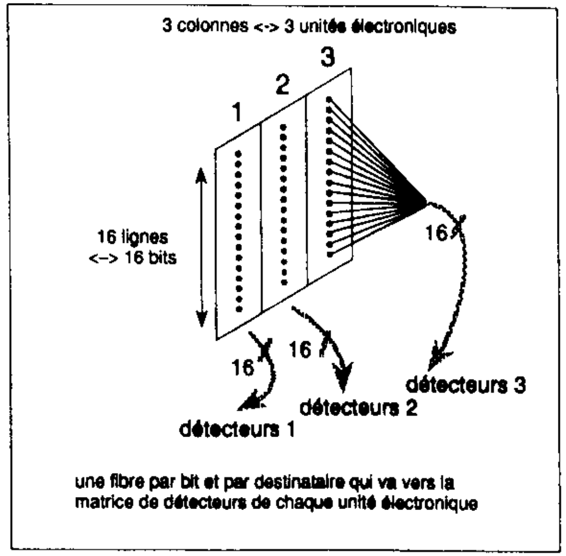
liaison optique d'une matrice de lasers vers 3 matrices de détecteurs



une fibre par bit vient de la matrice de lasers de chaque unité électronique

L : lentille de Fourier

plan de sortie



matrix of photodiodes for optical communication in free space

4 x 4 pixels
size = 15 µm
pitch = 125 µm

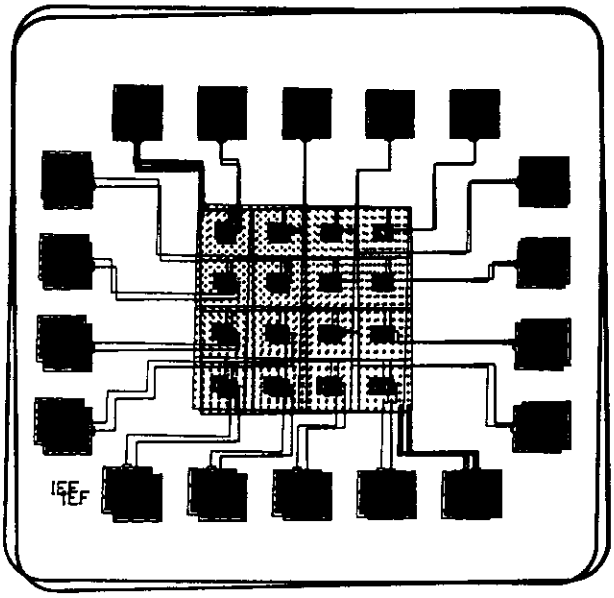
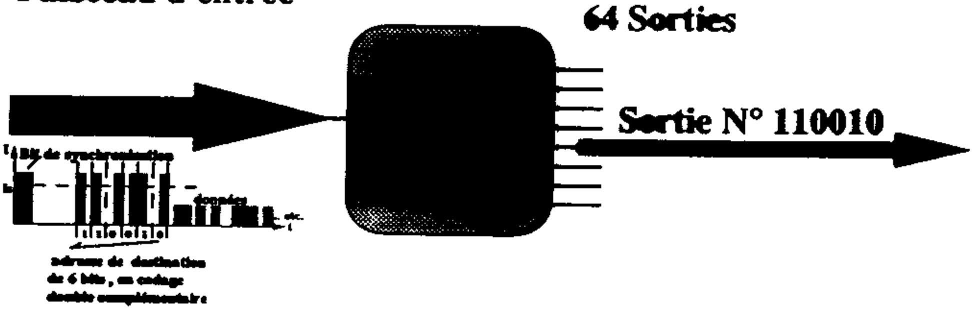


Figure 4 : 16 pixels matrix detector array

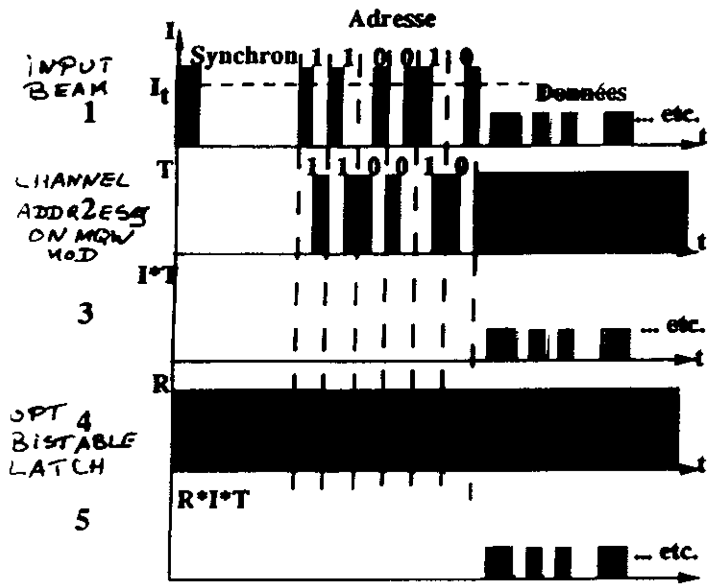
All optical packet switching on a 6 bit header
(20 MHz) clock, 12 cycles)

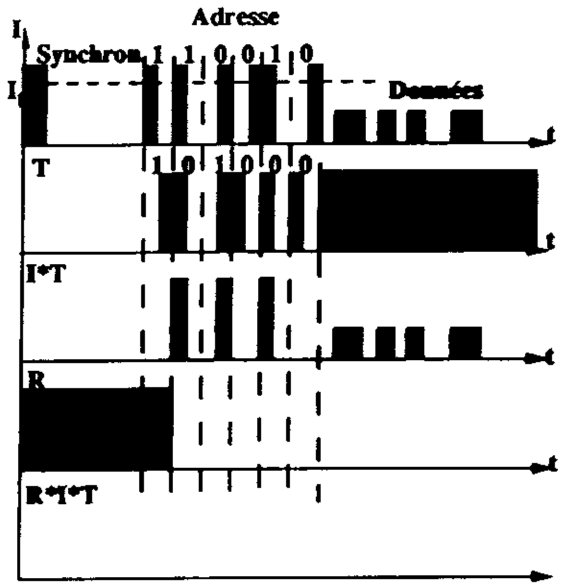
Le système démonstrateur : un autocommutateur pour signaux numériques organisés en paquets

Faisceau d'entrée



P. KOPPA





MOTS project
CNET France Telecom
Thomson CSF LCR
Institut d'Optique CNRS

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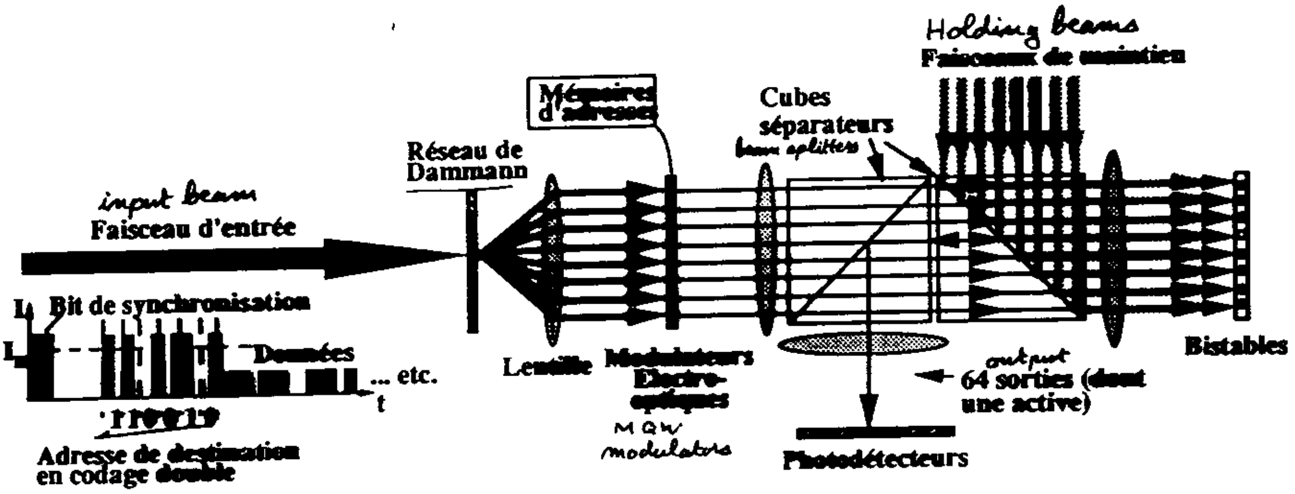
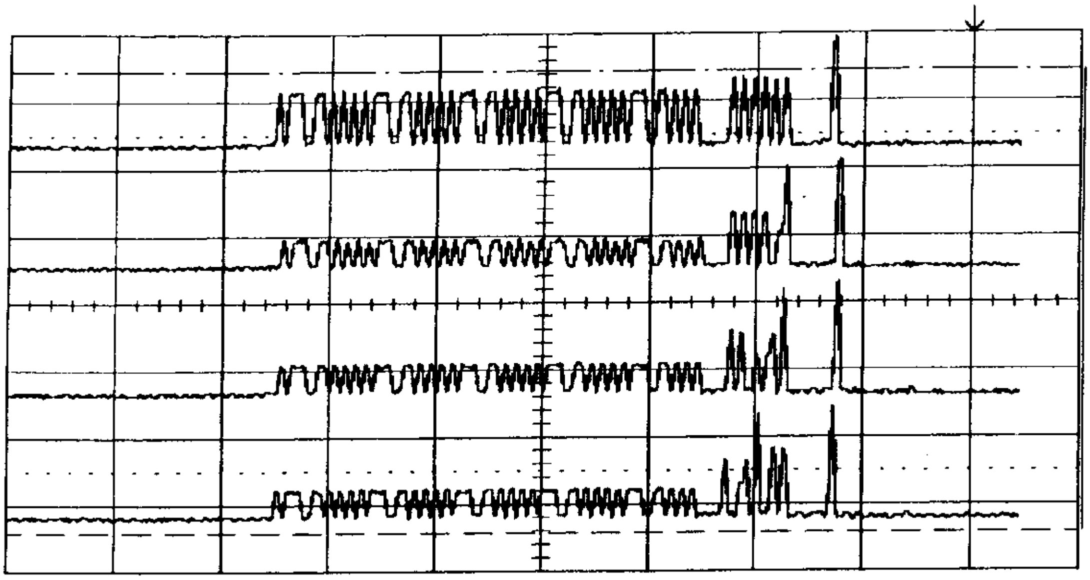
Principle of operation

Schèma de fonctionnement du système



ICTA
CNET
Thomson
1993 projet MOTS du Ministère ?



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The electronic interconnect hierarchy

1 - module to module
2 - backplane to backplane

→ (telecom. / L.A.N.) few, long, multiplexed → many, short, ...

3 - board to board
4 - chip to chip
5 - gate to gate

Réf.: J.W. Goodman et al., IEEE Proc. 72, 850 (1984)
J.W. Goodman, ICO XV, august 1990

DISCUSSION

- velocity of signal NO
- avoid to load capacitors YES
- no electromagnetic interference YES
- bandwidth YES
- free space, nb. of interc., parallelism YES
- fan-in / fan-out IRRELEVANT
- reprogrammability POTENTIALLY
- compactness ? progressing fast
- optical logic ? not in foreseeable future