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ADRIATICO CONFERENCE ON FOURIER OPTICS AND HOLOGRAPHY

ANALOGUE OPTICAL COMPUTING

NON LINEAR COUPLING

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ANALOGUE OPTICAL COMPUTING

NONLINEAR COUPLING

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INSTITUTE OF APPLIED PHYSICS

DARMSTADT / FRG.

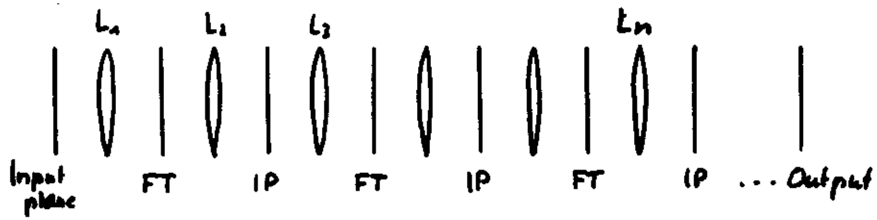
- MOTIVATION
- OPTICAL OPERATIONAL AMPLIFIER
- DEGENERATED WAVE MIXING
- PHASE CONJUGATION
- EFFECTS AND MATERIALS
- APPLICATIONS & PROBLEMS
- OPTICAL COMPUTER
- NEURAL NETWORKS
- FUTURE ASPECTS

1 MOTIVATION

OPTICAL INFORMATION PROCESSING :

- Parallel processing
- high processing speed
- no photon-photon interaction (lin. optics)
  → ideal interconnection
- photon-photon interaction (nonlinear optics)
  → coupling between channels

IMAGE TRANSMISSION- AND PROCESSING-SYSTEMS :



Examples : Mask projection , Correlators
Lens guide , Feedback systems

We need : • high space-bandwidth product

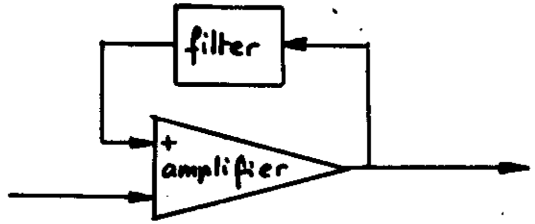
• Compensation of losses

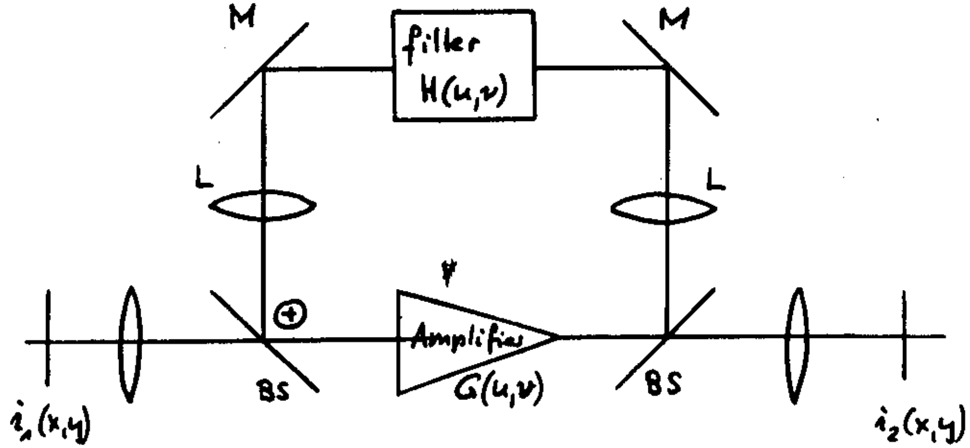
• Compensation of aberrations

2 OPTICAL OPERATIONAL AMPLIFIER

Programmable element :

Electronics : 1 dimensional
Optics : 2-4 dimensional

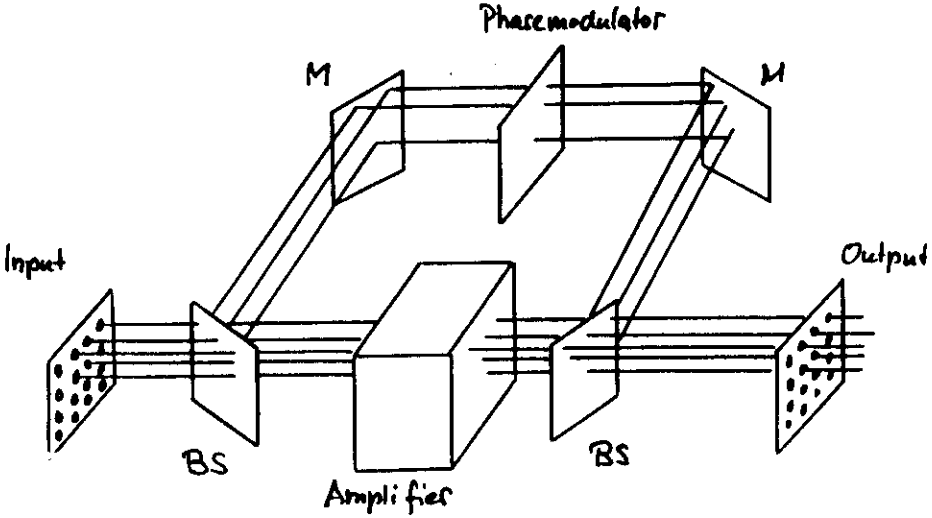




Transferfunction $T(u,v) = T(u,v)\{G(u,v)\,H(u,v)\,\alpha,\beta,e^{i\phi(u,v)}\}$

Phase amplifier : Quantum amplifier
Parametric amplifier

Optical feedback system: Operational Amplifier



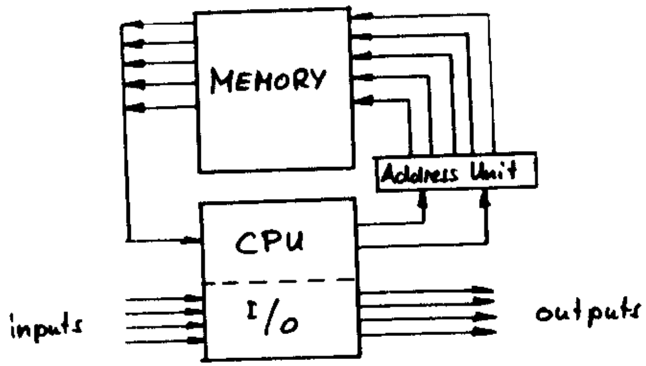
feedback + : Oscillator

— : Amplifier

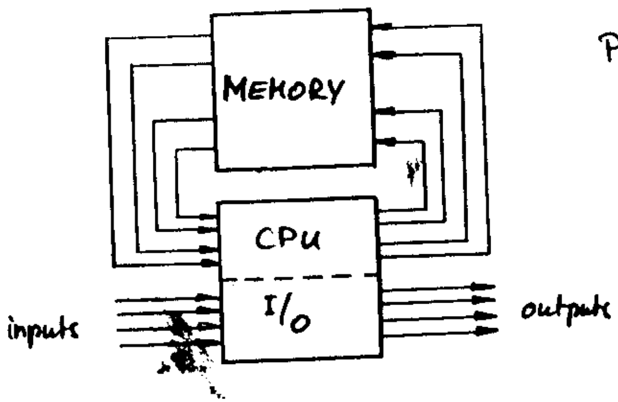
important elements: Amplifier
Phasemodulator

COMPUTER ARCHITECTURE

Von Neumann computer



Non Von Neumann Computer



PARALLEL PROCESSING

Limits: response time ~ psec
switching energy ~ pJ
pixel size
interconnections

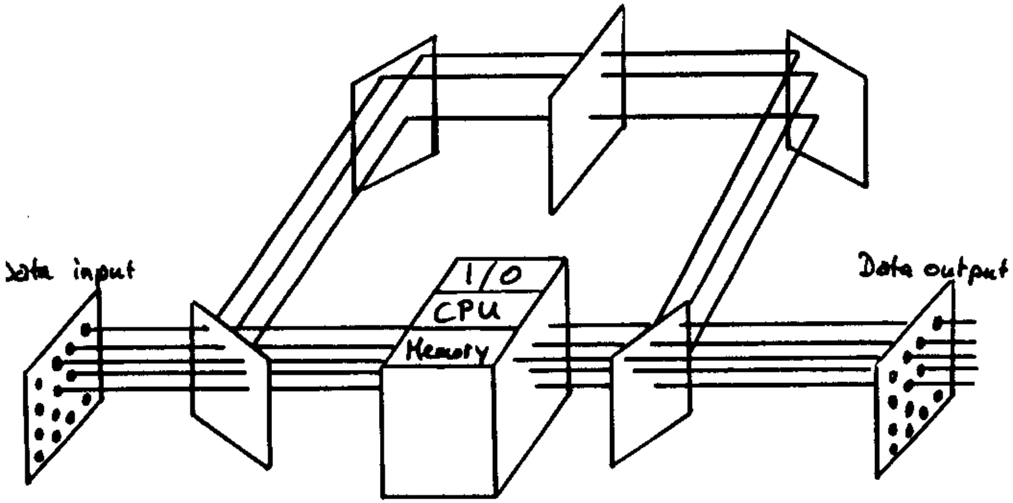
OPTICAL OPERATIONAL AMPLIFIER

Optical Information Processing

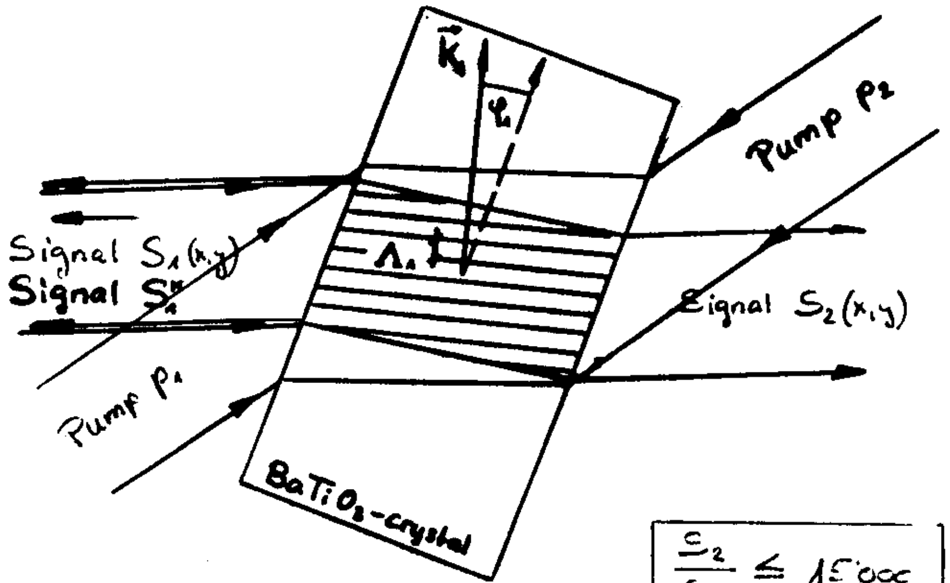
- analog : universal element → optical operational amplifier 

  associative memories
- digital : feedback loops in computer architecture

  interconnections



Degenerate 2- and 4 -wave mixing



$$\frac{S_2}{S_1} \leq 1500$$

$$\frac{S_1^*}{S_1} \leq 50$$

Experimental conditions:

$BaTiO_3$: $6.3 \times 2.4 \times 3.2\ mm^3$

λ = 514.5 nm cw Ar^+ laser

$P_1 \approx$ 100 mW

$S_1 \approx$ μW

$\tau \approx$ sec

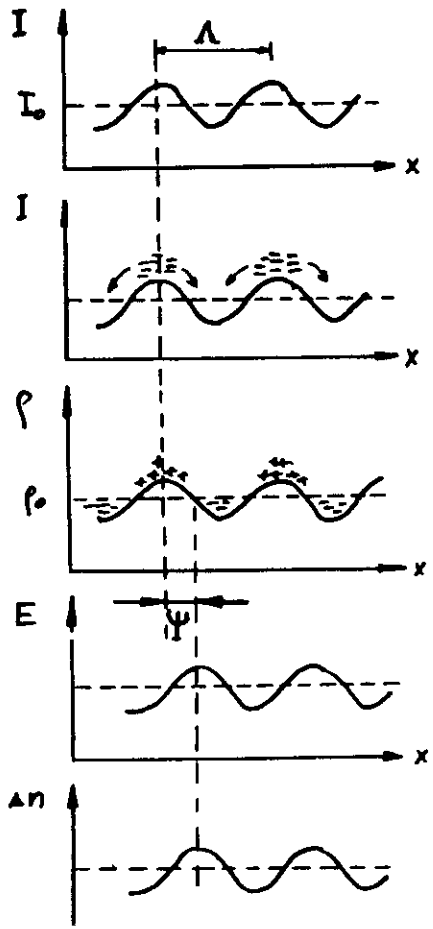
Linearer elektrooptischer Effekt (Pockels-Effekt)

Indexvariation : $\delta n = n_0^3 \, r \, \frac{E_0}{2}$

r : electroopt. Coeff.
E_0 : electric Field

Effect is slow (diffusion) nsec ... sec

z.B. in $LiNbO_3$, $LiTaO_3$, $BaTiO_3$ etc
CdS, $CdTe$, $Bi_{12}SiO_{20}$ etc



Illumination
$I(x) = I_0 (1 + m \cos kx)$

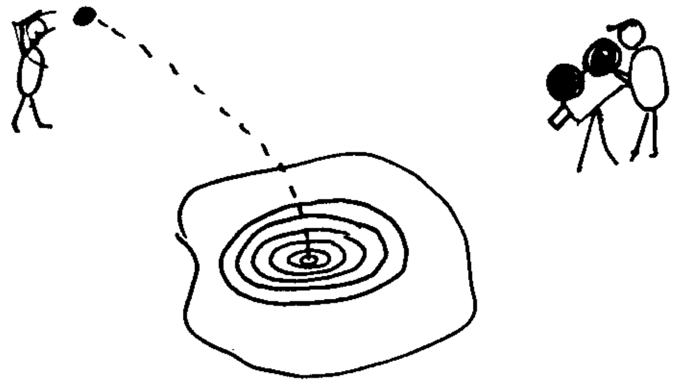
charge production
$N(x) = N_0 (1 + m \cos kx)$

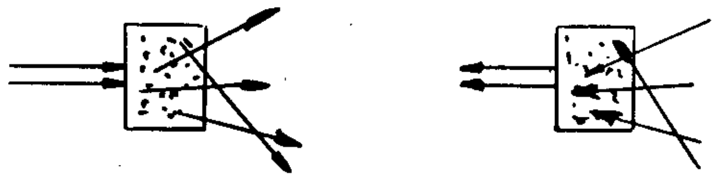
Migration, Diffusion
$\rho(x) = \int_0^t \frac{dJ}{dx} \, dt$

space charge field
$E(x) = \int_0^x \frac{\rho}{\varepsilon} \, dx$

Index variation
$\Delta n = n_0^3 r E$

What is a phase-conjugated wave ?





plane wave

$$E_{real}(R,t) = |E(R)| \cos [\omega t - \phi(R)]$$

local amplitude — local phase

$$E_{conj.}(R,t) = |E(R)| \cos [-\omega t - \phi(R)]$$

$$\equiv |E(R)| \cos [\omega t + \phi(R)]$$

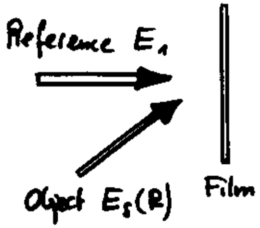
$$\phi(R) \Longrightarrow -\phi(R)$$

time reversal is equivalent with sign change in phase (for each point in space)

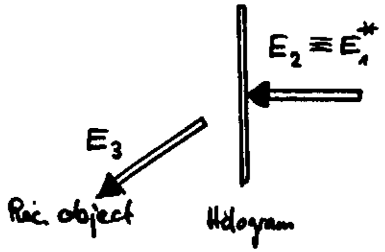
How to generate a phase-conjugated wave

Holography

1. Recording



2. Reconstruction

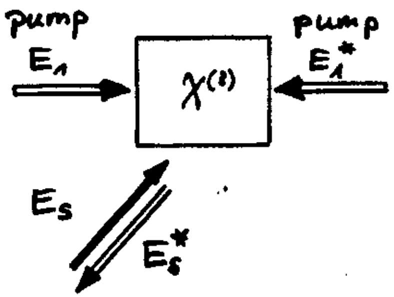


$E_3(R) = E_s^*(R)$

Phase-conjugation

Simultaneous recording and reconstruction in $\chi^{(3)}$ media

$\omega_1 = \omega_2 = \omega_3 = \omega_4$ degenerate FWM

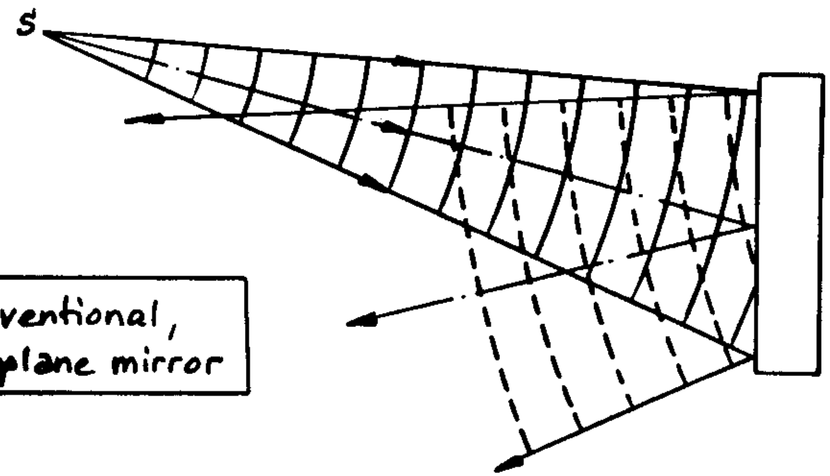


Rec.: $\delta t(r) = \text{const}\left[E_1^*(r)E_s(r) + E_1(r)E_s^*(r)\right]$ | $\delta\rho(r) \sim E_1^*(r)E_s(r) + E_1(r)E_s^*(r)$

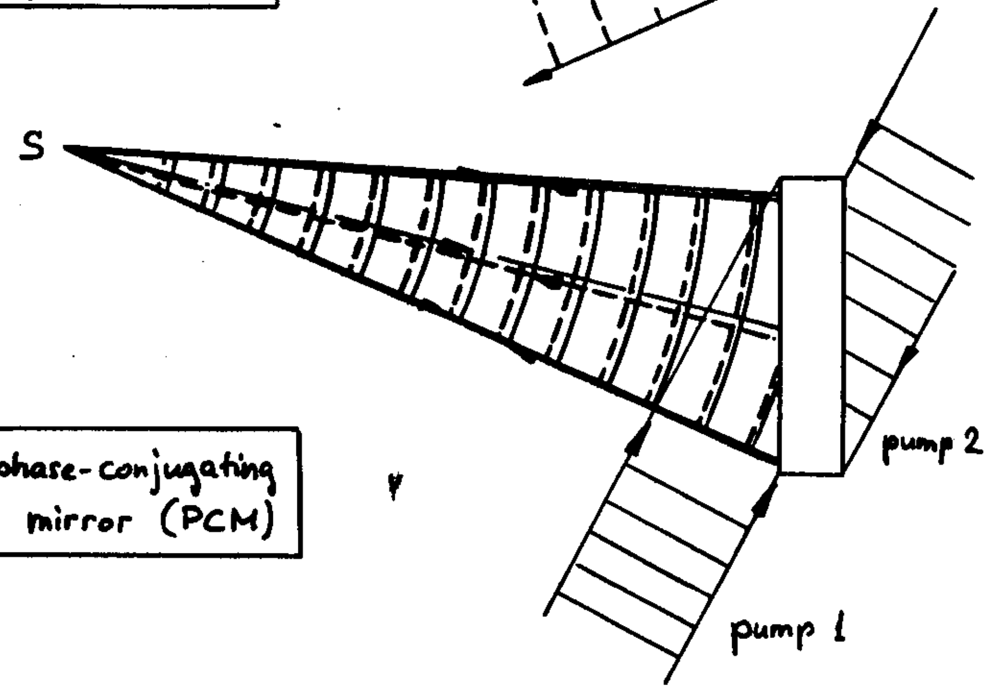
Reconstr.: $E_3(r) \sim |E_1|^2 E_2^*(r) = |E_1|^2 E_s^*(r)$ | $E_3(r) \propto E_1^2(r) \cdot E_s^*(r)$

R : x, y, z

r : x, y



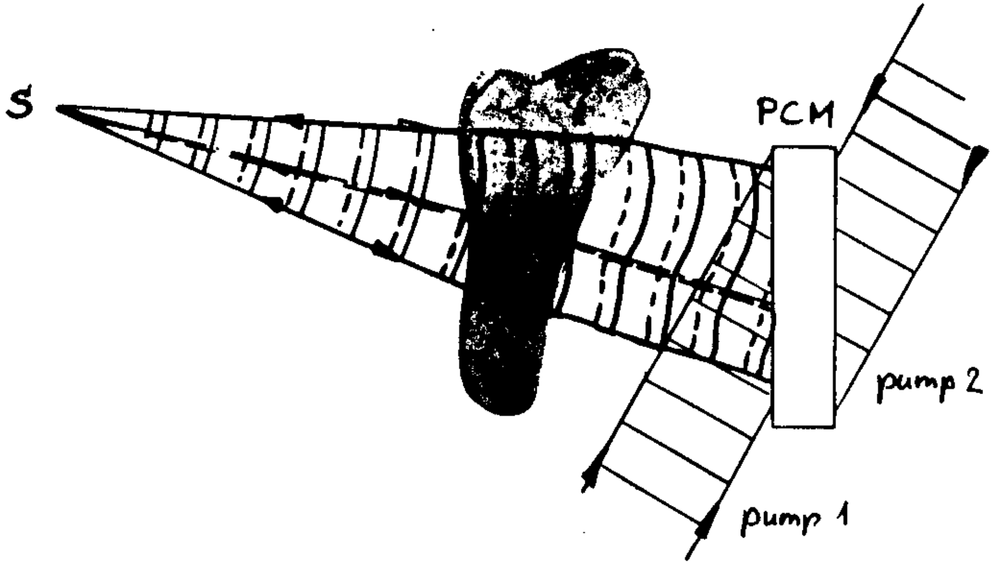
conventional, plane mirror



phase-conjugating mirror (PCM)

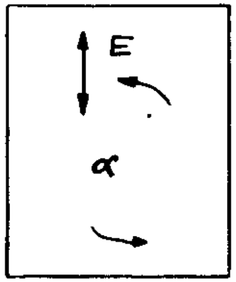
The PCM "reflects" the light in a "time reversed" sense

PCM for compensation of aberrated wavefronts



Intensity dependent changes in the index of refraction

Kerr effect

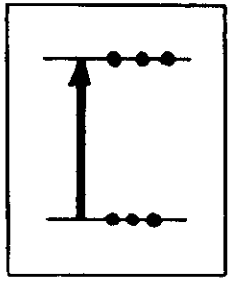


liquid crystals

$n_2 = 10^{-8}$ esu

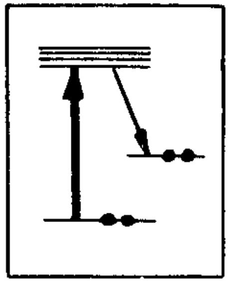
$\tau \sim$ nsec ... sec

Saturation



bleaching

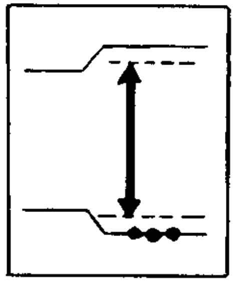
Opt. pumping



metastable state

$n_2 = 10^{-4}$ esu at 10^{13} at/cm^3

Light shift

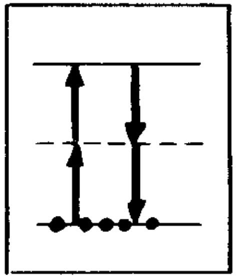


opt. Stark effect

el. Kerr effect

$n = 10^{-8}$ esu in Na

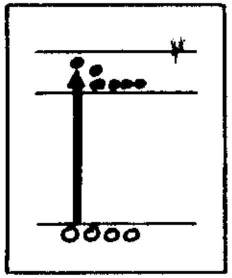
Two photon



$n_2 = 10^{-10}$ esu in Na at 10^{14} at/cm^3

$\tau = 30$ nsec

Photoconduction

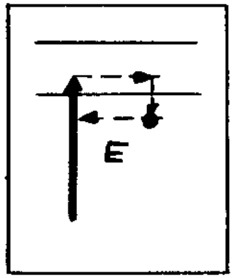


Semiconductors

free carriers will alter plasma freq → Δn.

$n_2 = 10^{-6}$ esu in Si at 1.06 µm

Photorefraction



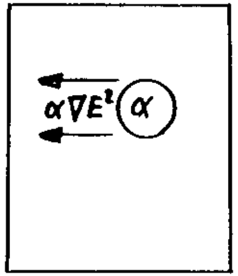
Separation of mobile carriers

→ Pockelseffekt

high sensitivity

slow response

Radiation force



Suspended particles

⇒ density variation

$n_2 = 10^{-6}$ esu

$\tau \sim 400$ msec

Mechanisms and materials

FWM: $E_4 \sim \chi^{(3)} E_1 E_2 E_3^*$

- Orientation of Molekules
- NL-saturation
  - resonant gases
  - absorbing dyes
  - thermal effects
  - gain saturation
- Nonlinear semiconductors, incl. photorefractive crystals
- Stimulated Brillouin scattering and parametric SBS

Materials:

λ	Laser	Interaction	Medium	Reflectivity	Power
10μm	CO_2 pulsed	DFWM	SF_6 2cm	37%	200 kW/cm²
		DFWM	HgCdTe 0.5mm	10%	100 kW/cm²
		DFWM	Ge 15cm	25%	10 MW/cm²
1.06μm	Nd YAG	DFWM	Si 1mm	180%	6 MW/cm²
		SBS	CS_2, CH_4	90%	
0.532μm	Nd YAG	DFWM	Rhodamin	100%	
0.48μm	Ar^+ cw	DFWM	$BiSiO_4$	1%	$3 \cdot 10^3$ J/cm³
		DFWM	$KNbO_3$		
0.514μm	Ar^+ cw	DFWM	$BaTiO_3$	>100% [W]	10^3 J/cm³
0.633μm	HeNe	DFWM	BTO	>100% [mW]	

Important parameters:
- sensitivity
- time constant
- availability

Optical Switches

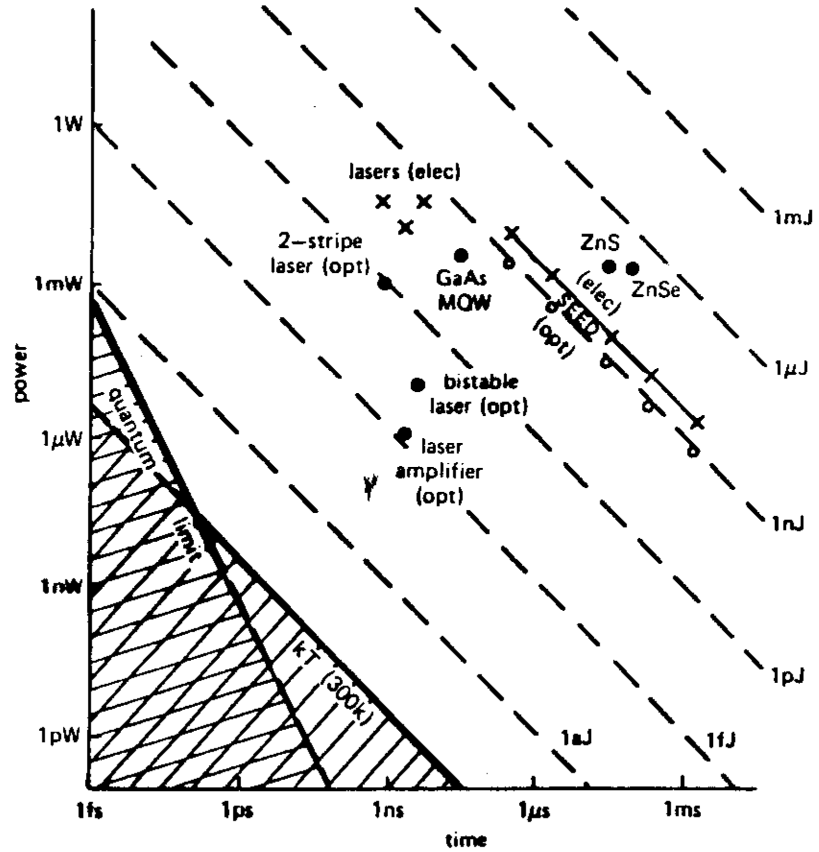


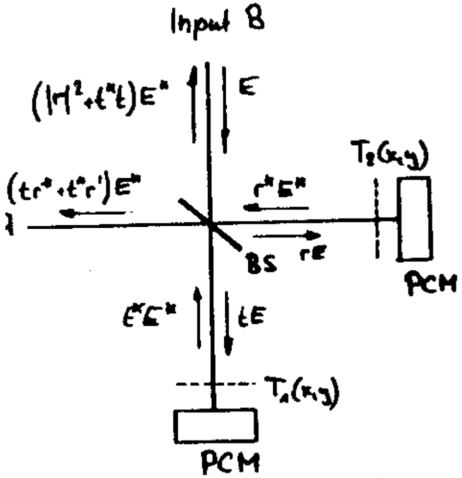
Fig. 6 — Power versus time for best reported bistability results in semiconductors. (For details see Adams M.J. (1986) in 'further reading').

Opt. computing applications, image processing

2- and 4-wave mixing
Phaseconjug. mirrors
Phaseconjug. Interferometers

} Image subtraction, exclusive or, intensity inversion — spatial diff., temporal diff., etc.

Image subtraction



Recombination of PC waves in BS then output A:

$$I_A(x,y) = |E|^2|\rho|^2\left|t^*r'T_1(x,y) + r^*t\,T_2(x,y)\right|^2$$

ρ : refl. coeff. of PC

with Stokes: $(R = |r|^2\ ;\ T = |t|^2)$

$$I_A(x,y) = |E|^2|\rho|^2\, RT\,\left|T_1(x,y) - T_2(x,y)\right|^2$$

e.g. demonstration in $BaTiO_3$ by P. Yeh or Yariv

Matrix operations by four-wave mixing

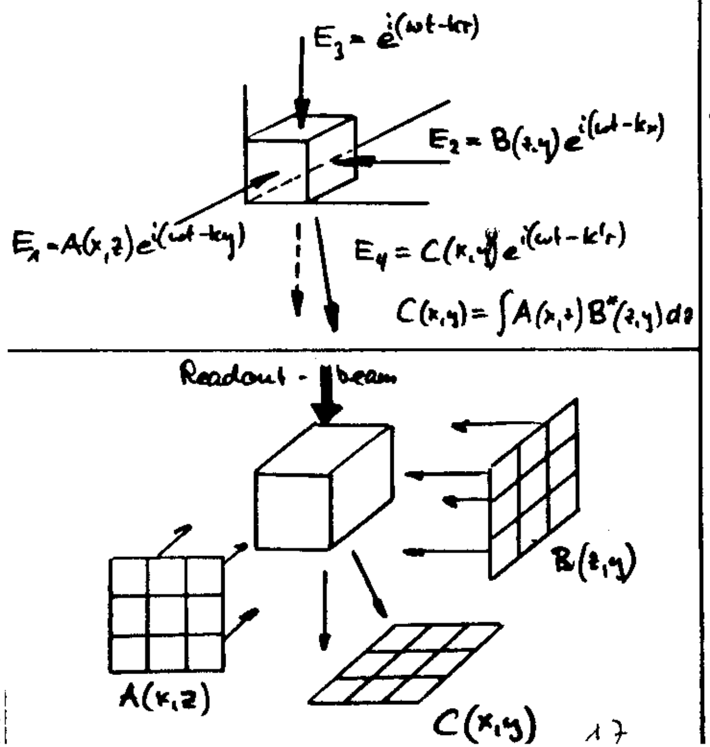
e.g. proposed by P. Yeh or Yariv ....
matrix · matrix, matrix · vector — Coupling!

degenerate 4-wave-mixing: $E_4 \sim \chi^{(3)} E_1 E_2 E_3^*$
⇒ multiplication of signals

matrix multiplication: $C = AB$

where $$C_{ij} = \sum_k A_{ik} B_{kj}$$

1. parallel multiplication
2. Summation



In NL-media:
Information in volume grating:
$\Delta n = n_2 A(x,z) B^*(z,y) e^{ikr} + cc$

n_2 : Kerr coeff $\sim \chi^{(3)}$

read out by 3. beam (plane wave)

$$C(x,y) \propto \int A(x,z) B^*(z,y) dz$$

integration along beam path

limiting factor: crosstalk

Realization of an optical operational amplifier

- high gain
- compensation of aberrations
- high space-bandwidth-product

Magic-T in combination with a PCM

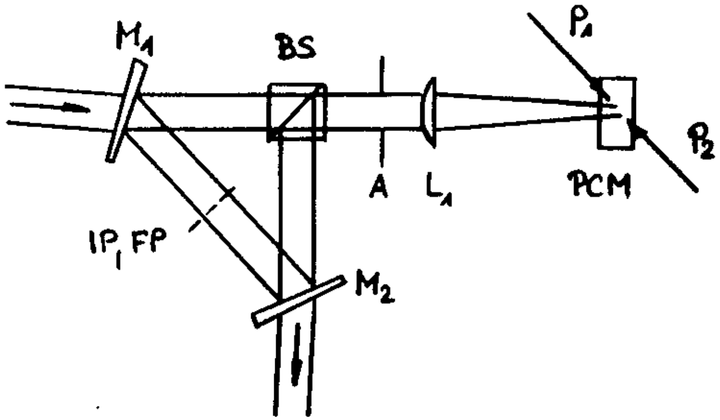


Image - Amplifier
Image - Oscillator

- Coupling between channels is possible
- grade of feedback (+ -) by a phase modulator (n_3)
- interconnection between channels by "
- 1-way operation by mean of polarizing elements
- " add. gain by 2-wave-mixer

5. Some Problems

Nonlinear optical material:

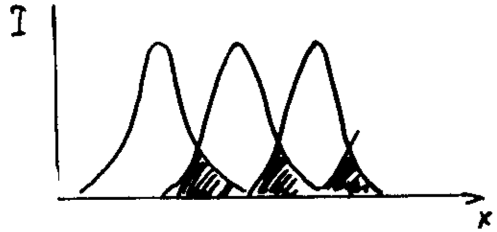
- high nonlinear optical coefficient
- high sensitivity ($\lambda = 0.3 \dots 1.5\ \mu m$)
- fast response $BaTiO_3$ ... sec   ... kW/cm²

- optical homogeneity
- low scattering
- preparation of the material
- low costs

→ NEW MATERIALS

Feedback system:

- time constant $\tau_R < \tau_m$; $\tau_R > \tau_m$
- coupling between channels



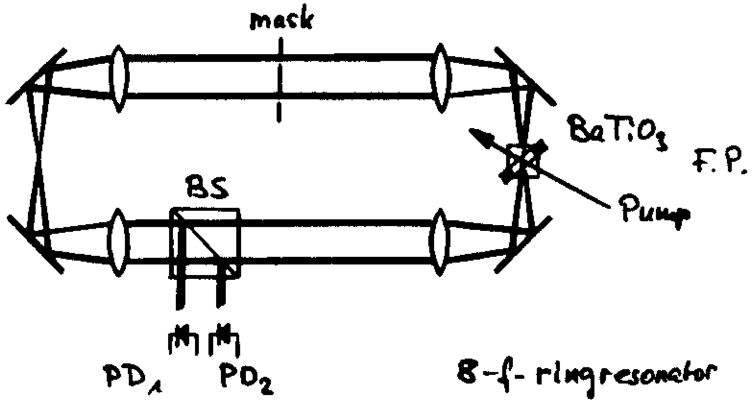
coupling through nonlinear medium.

- image plane
- fourier plane

! ⊕ and/or ⊖ !

Coupling channels in a photorefractive ring-resonator with gain provided by two-wave mixing

Experiment: three-wave mixing for applications in thresholding, switching, and amplifying

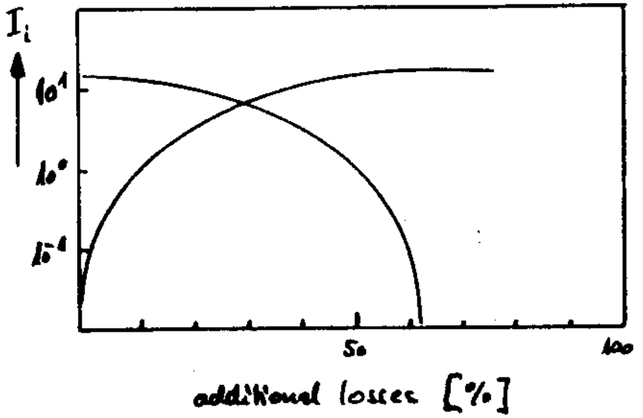


Losses L_i = 90%

Gain G_i = 246%

Example: $\Delta I_1 = 0.04$ $\Delta I_2 = 100$

Self oscillation ↔ strong coupling!



6 APPLICATIONS

1. Feedback systems; opt. oper. amplifier
   - image amplifier
   - image oscillator
   - beam shaping / forming systems
   - adaptive filters
   - iterative systems

2. Coupling between channels

   Profile overlapping of pixels in the nonlin medium

   Overlapping of space-frequencies in nonlin medium

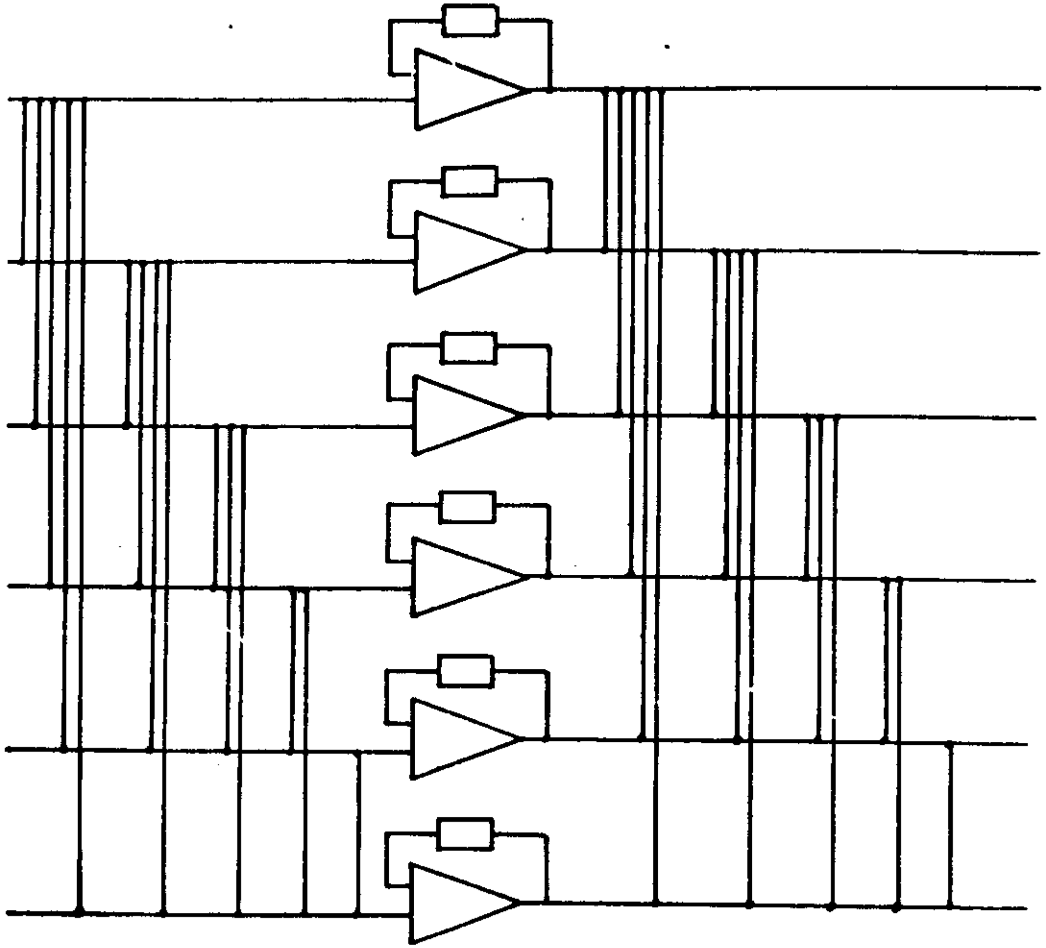
   ⟹ Array of coupled oscillators ($10^5 \ldots 10^7$ channels)

   → Nonlinear dynamics of coupled systems

   Simulation of complex multidimensional coupled systems:
   - spatial / temporal behaviour
   - stabilities / instabilities
   - evolution of structures (e.g. from noise)
     periodic, aperiodic, chaotic behaviour
   - self reparation

   ⟹ Simulation by analog optical computing

Array of coupled amplifiers / oscillators

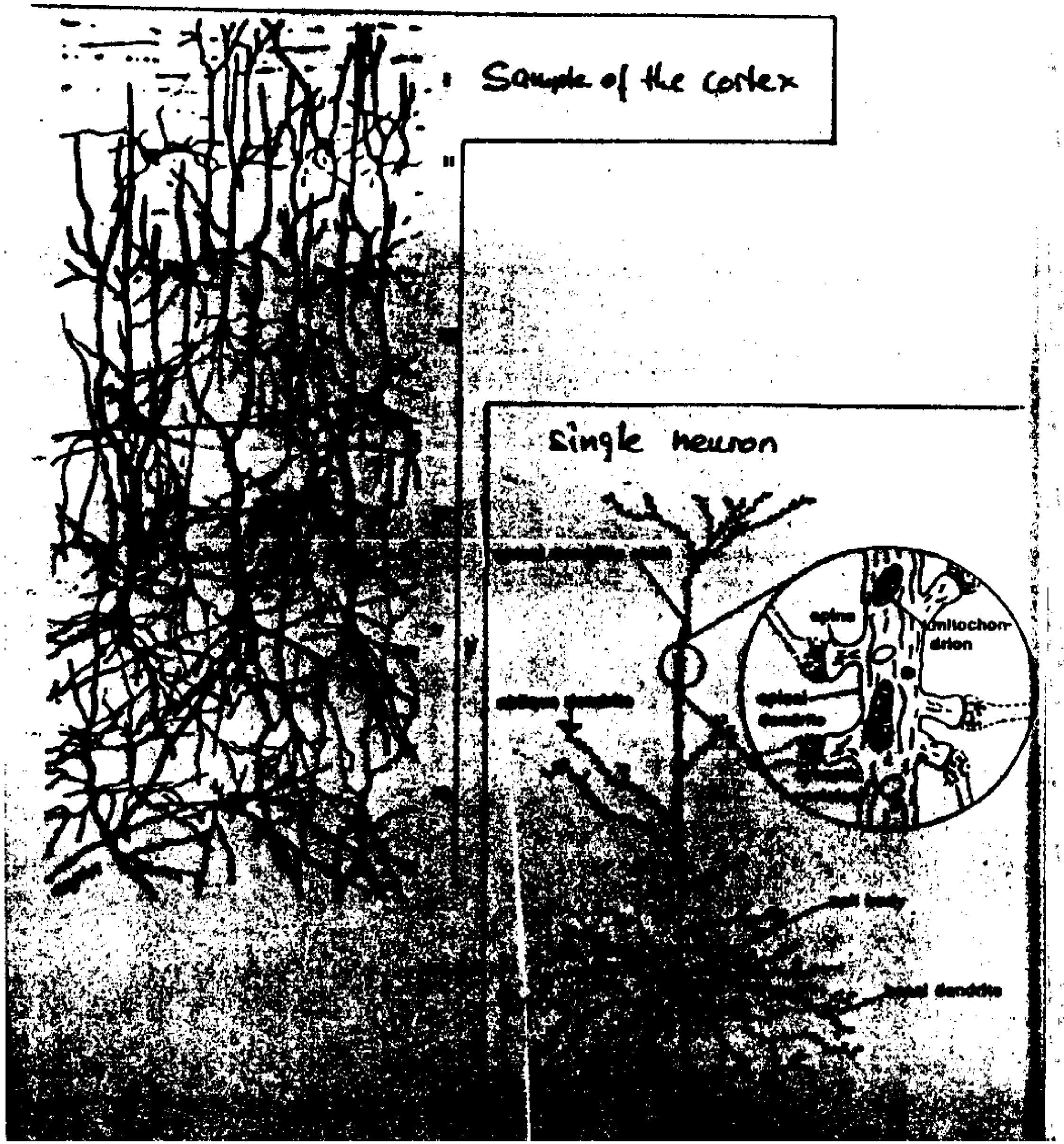


ARRAY VON LINEAR / NICHTLINEAR GEKOPPELTEN NICHTLINEAREN SYSTEMEN

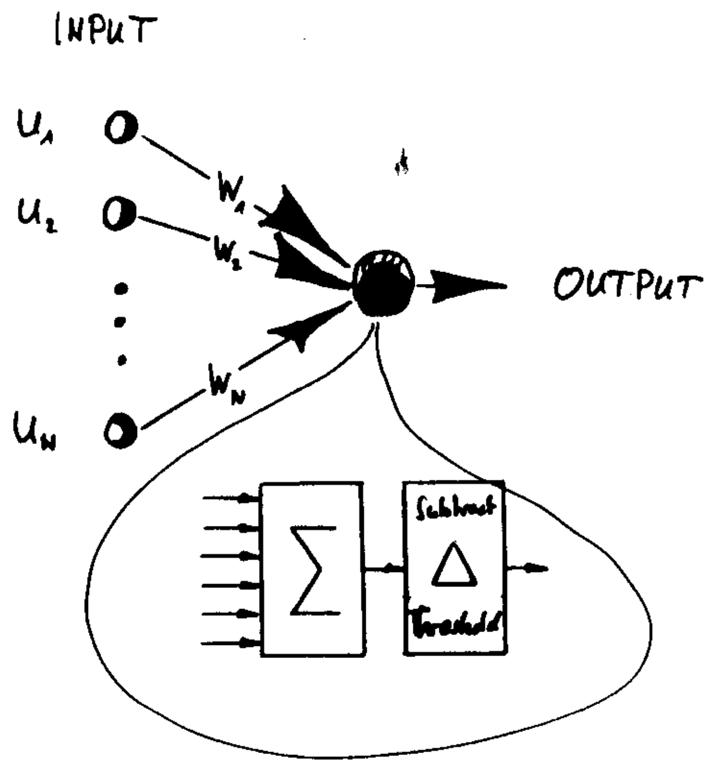
$10^5 \ldots 10^6$ channels !

ASSOCIATIVE MEMORIES
NEURAL NETWORKS

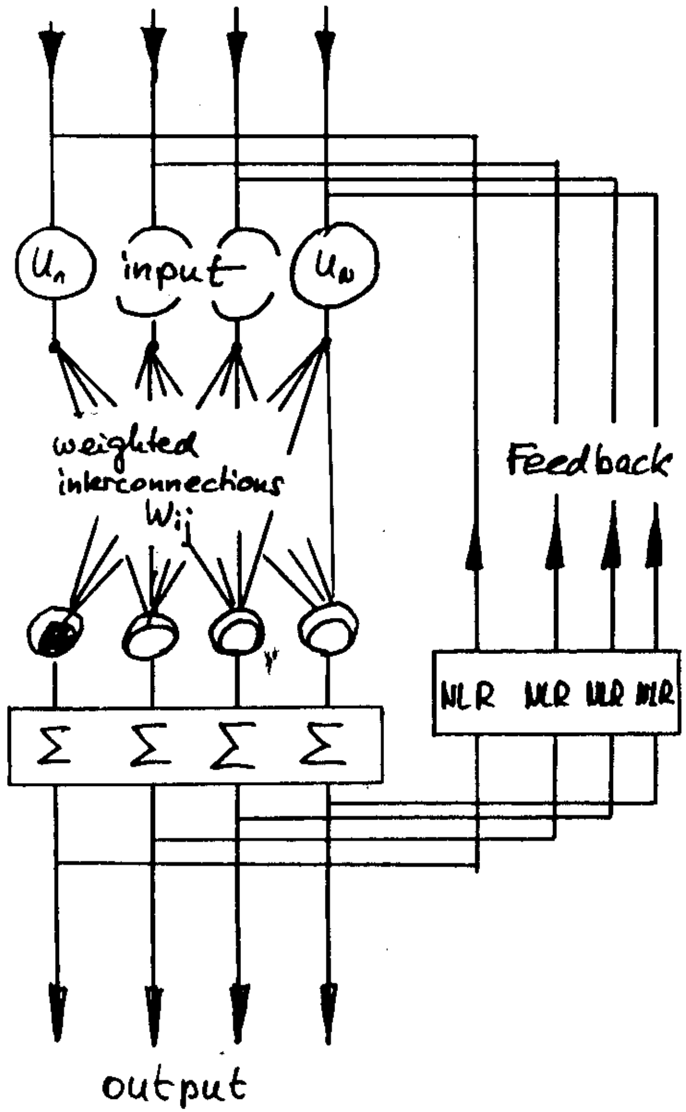
ARTIFICIAL INTELLIGENCE



SCHEMA OF A NEURON



Simple neural network



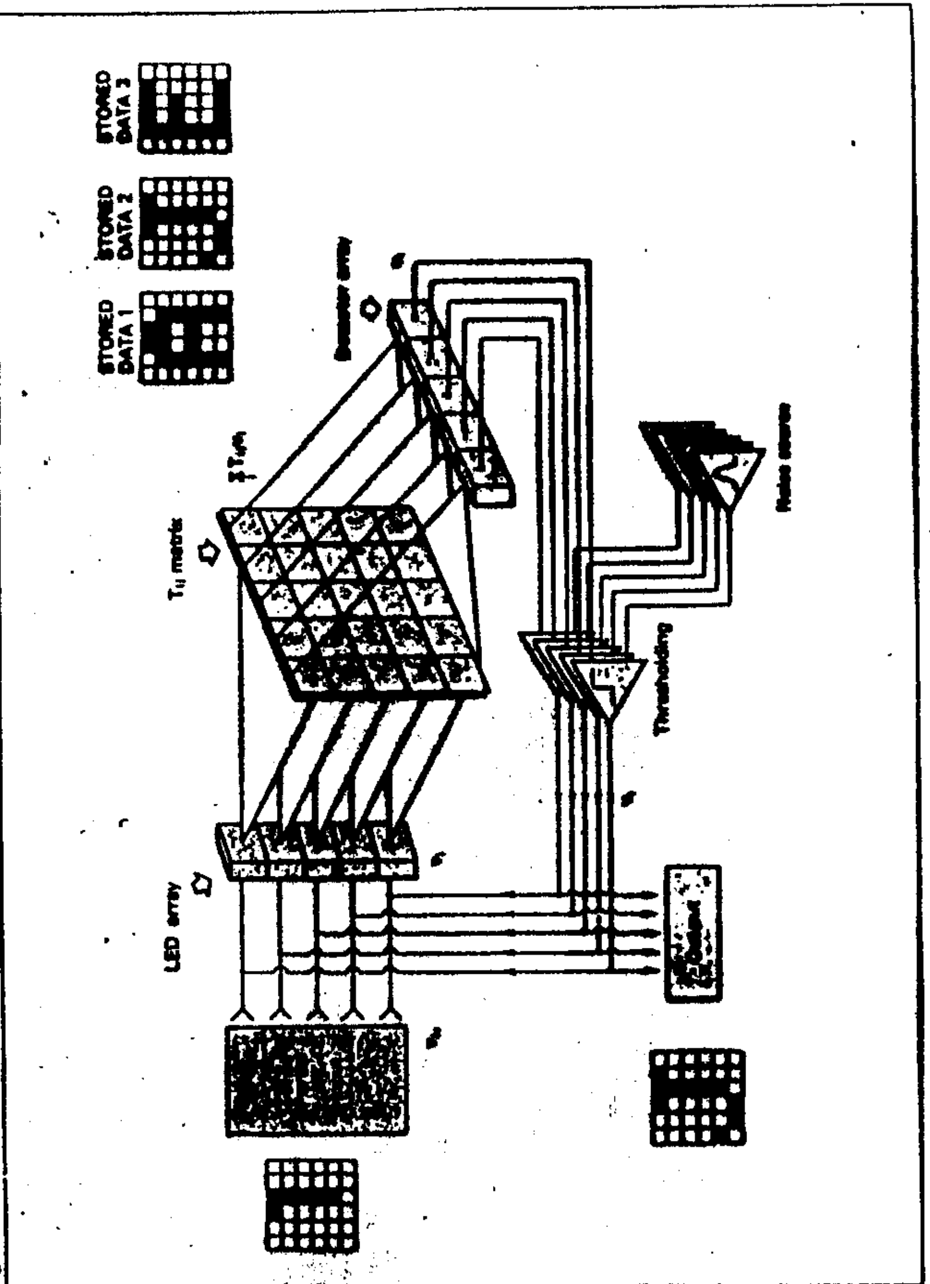
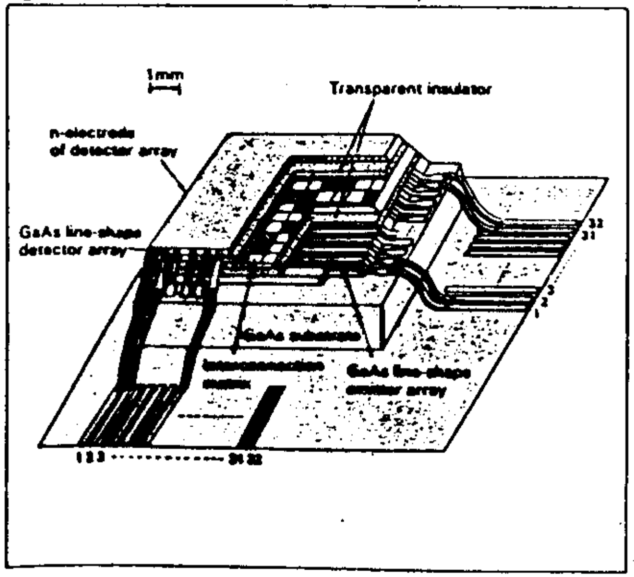
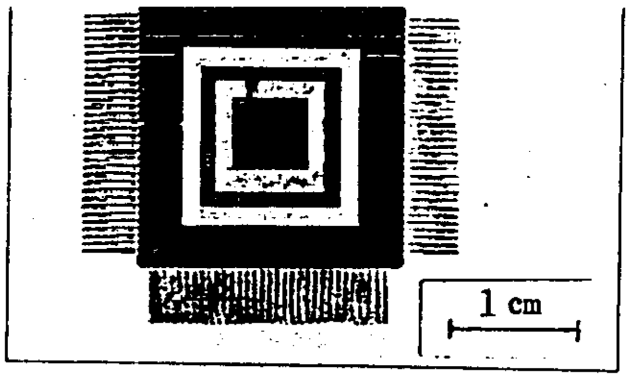


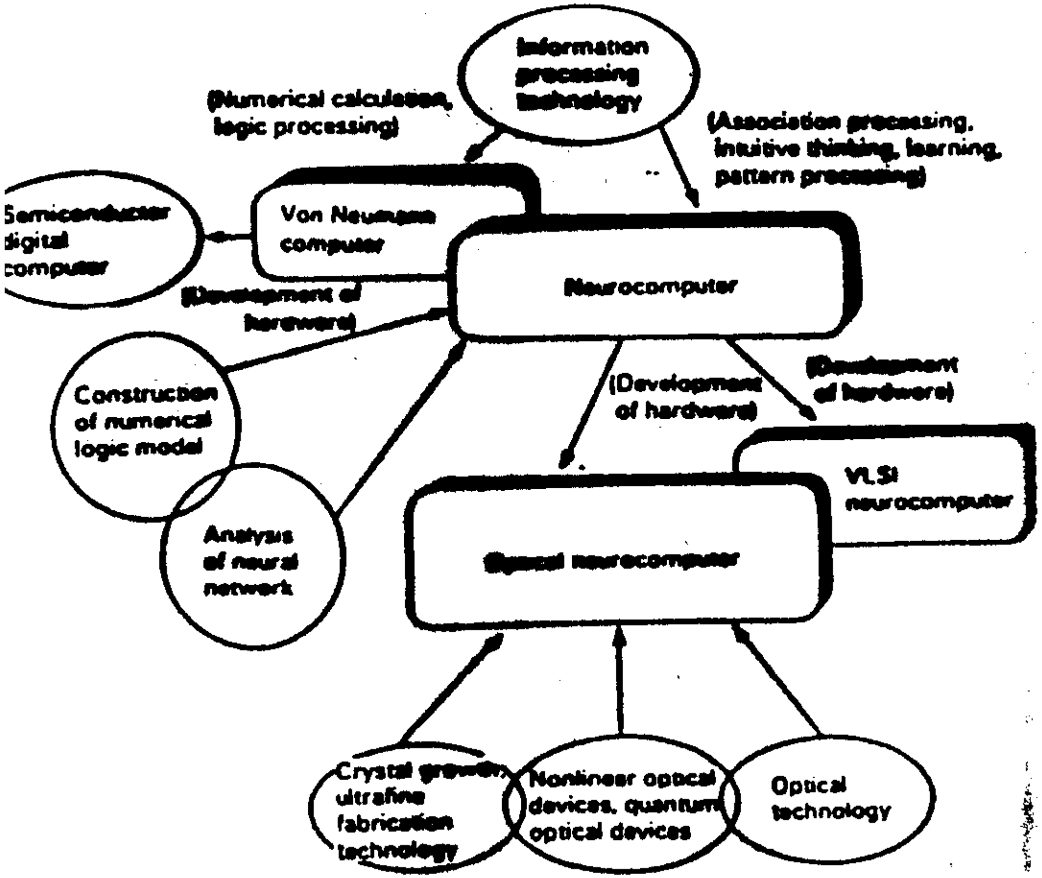
Fig. 2: Basic architecture of association optical neurocomputer utilizing statistical processing

Fig. 3: Basic structure of an optical neurochip





Optical neurocomputer in information processing technology



CONCLUSIONS

- Optical 2-D feedback systems with high space-bandwidth-product ($\sim 10^6$) and high gain is realised.
- Now slow, τ typically sec with photorefractive crystals
- in future: organic materials with high sensitivity and shorter τ
- We presented first simple experiments to investigate coupled nonlinear oscillator systems (e.g. for simulation and modelling)
- The system is useable in optical computing (feedback networks and puls restoring)

Information processing
Beam forming
Study of nonlinear coupled systems
associative memories
neural networks

ANALOG OPTICAL COMPUTING

Optical computing:

- Parallel processing   2-4 Dimensions
- Good interconnections between channels (holograms)
- Nonlinear processing
- functional oriented langague

Analogue Computers	Digital computers
Measuring technique	computing
Image Processing	
Adaptive Filters	
Simulations	

Both in combination with electronics