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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

H4.SMR/540-28

Second Training College on Physics and Technology of Lasers and Optical Fibres

21 January - 15 February 1991

Integrated Optoelectronics

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Gent, Belgium

Trieste, Feb 11-12, 1991

INTEGRATED OPTOELECTRONICS

R. BAETS

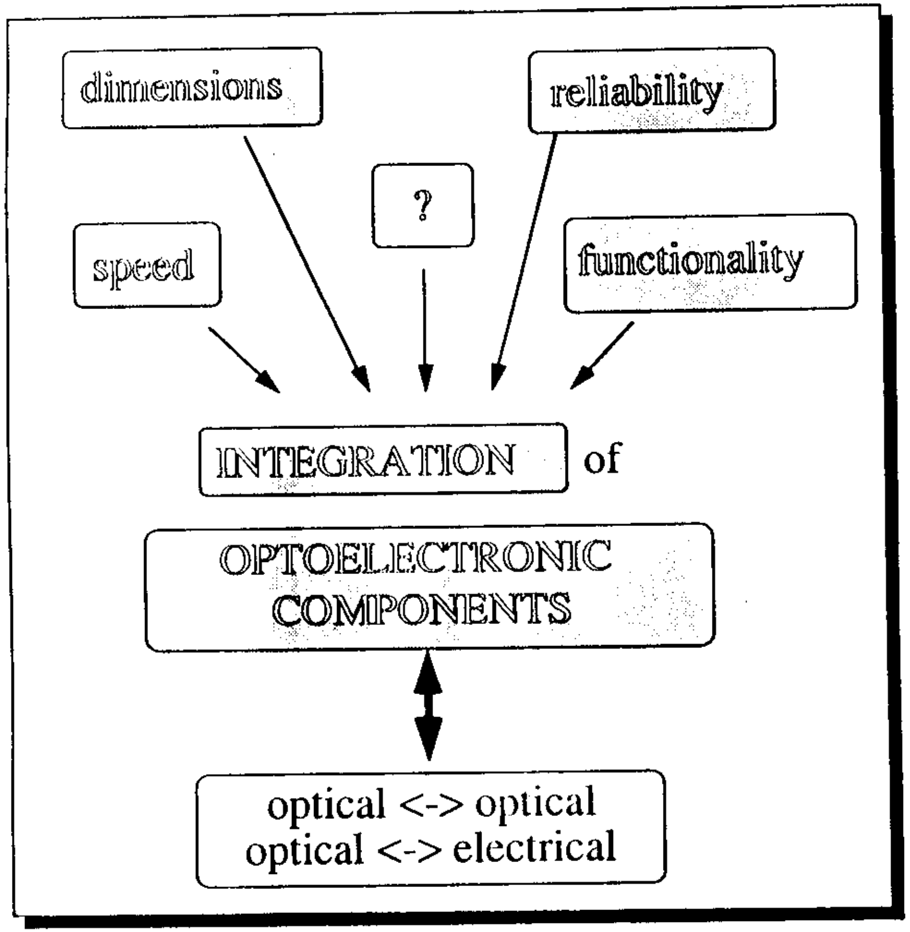
University of Gent
Belgium

TOPICS

- INTEGRATION : WHY?
- BUILDING BLOCKS : DEVICES
- INTEGRATION TECHNOLOGY
- EXAMPLES
- MODELLING

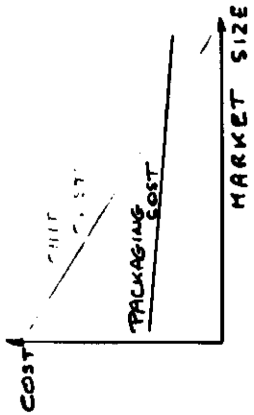
Introduction

LEA



INTEGRATION VERSUS PACKAGING

- Electronic Integration/Packaging



⇒ INTEGRATION WINS FOR LARGE VOLUME MARKETS

- Optoelectronic Integration/Packaging
  - Packaging at optical interface is difficult
  - Integration of dissimilar devices is difficult

⇒ Advanced Integration Technology needed
⇒ very expensive technology
⇒ high volume markets needed

Introduction

communications and datastorage

ever increasing demands on:

* data quantity
* speed
* reliability

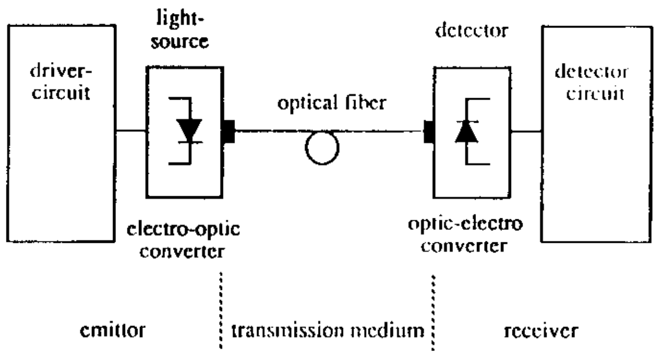
we already have:

* high performance transmission media (fibers)
* high performance sources (laserdiodes)
* high performance receivers (detectors)
* high performance electronics

Introduction

Important field of application:

Optical transmission

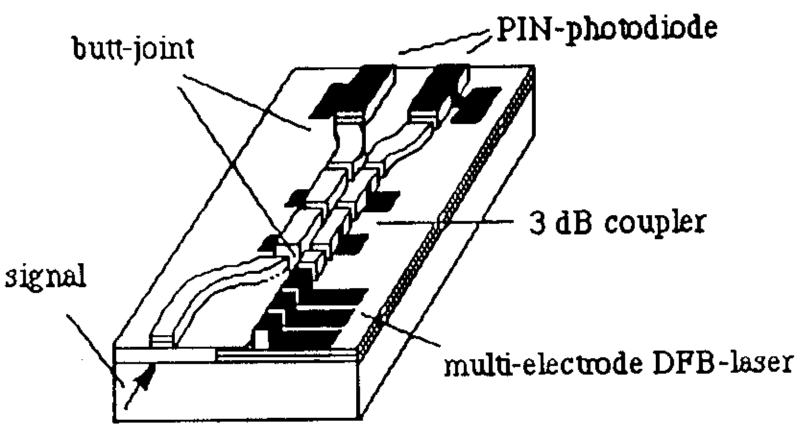


optical communications (fibers)
optical networks (LAN)
optical interconnect
optical computing
....

Introduction

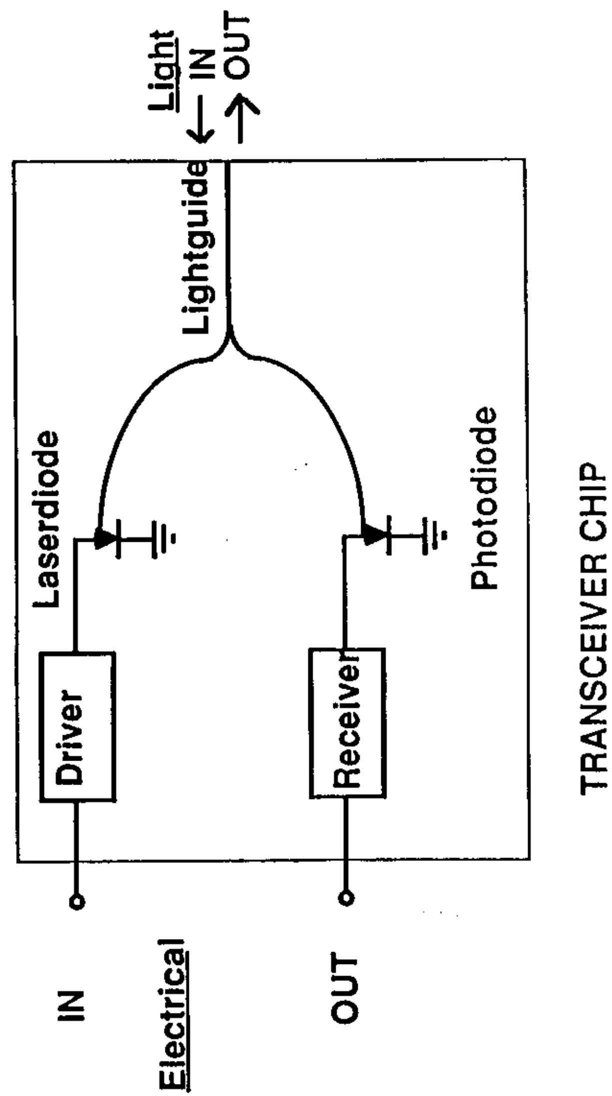
integration soon leads to very complex circuits

integrated receiver for coherent communication



(NTT-Japan, AT&T-USA)

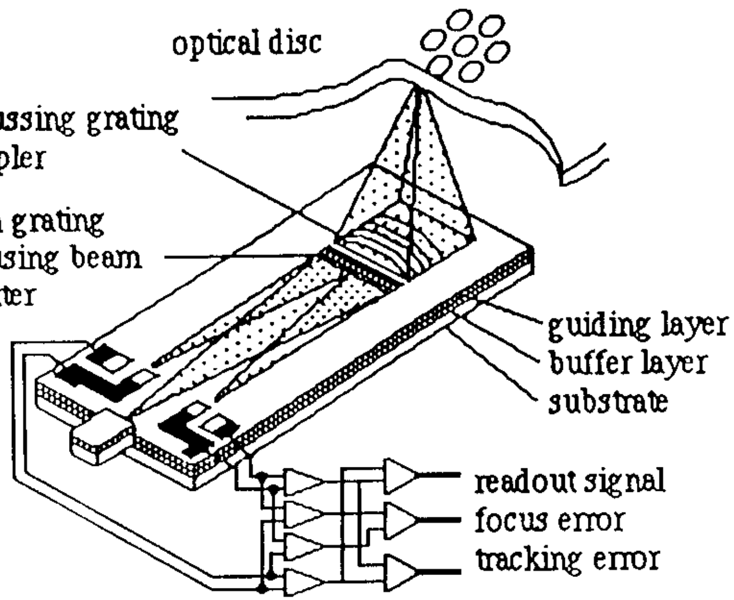
OEIC FUNCTION



Introduction

optics is more than optical communications

optical head for optical discs



TERMINOLOGY

CONFUSION – NO STANDARD

OEIC : Optoelectronic IC
= Integration of electronic circuits with optoelectronic devices
(few optical interfaces)

PIC : Photonic IC
= Integration of active and passive optoelectronic devices
(mainly of waveguide type)
ATT-Bell Labs terminology

IOC : Integrated Optic Circuit
= Integration of planar waveguide devices (mainly passive)

Building blocks

Electronic components

* transistors

Si - GaAs -...

Optoelectronic components

* light sources
* detectors

III-V - Si -...

Optical components

* waveguides
* optical switches

LiNbO3 - III-V -....

Building blocks

Electronic components

bipolar - field effect (FET)

JFET	Si GaAs	... ...
MOSFET	Si GaAs	(N) (P) (C) MOS, ...
MESFET	Si GaAs ...	 ...

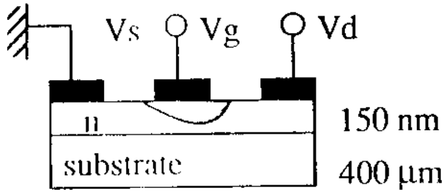
Si, III-V

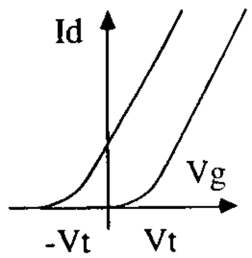
Si: integration = materials problem

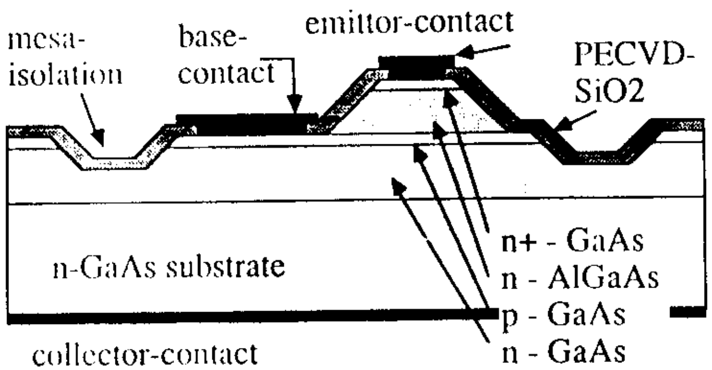
GaAs: integration = structural problem

2 - Building blocks

GaAs
MESFET <-> HBT





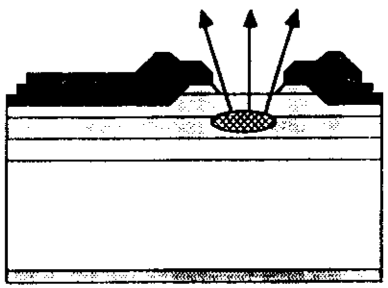


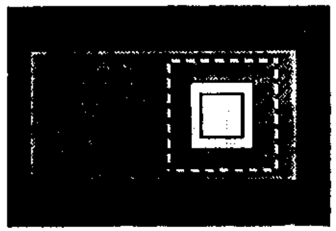
2 - Building blocks

Optoelectronic components

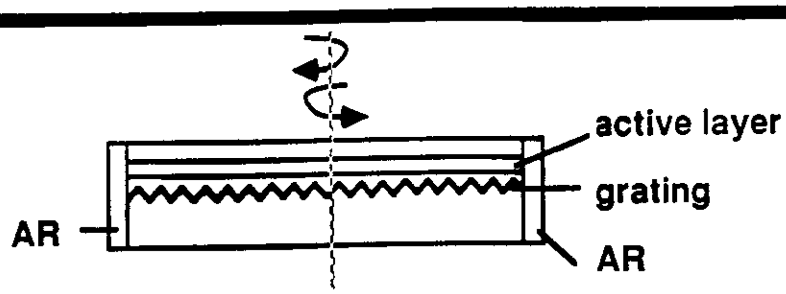
Lasers, LED's, Detectors

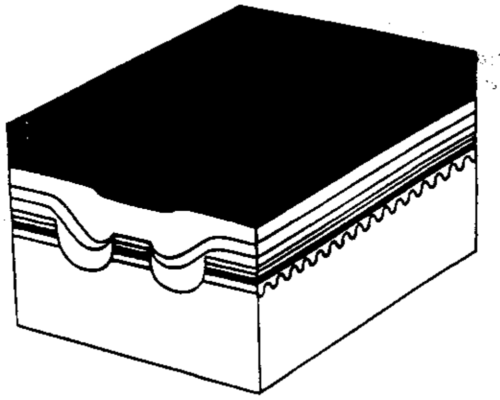
III-V





SLM LASERS
DISTRIBUTED FEEDBACK (DFB) LASER

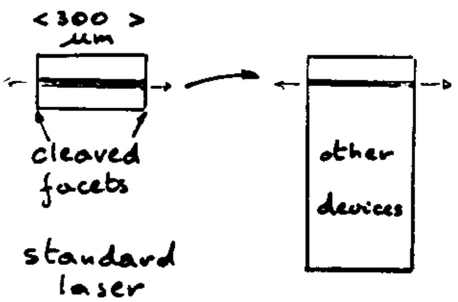




DCPBH - LASER

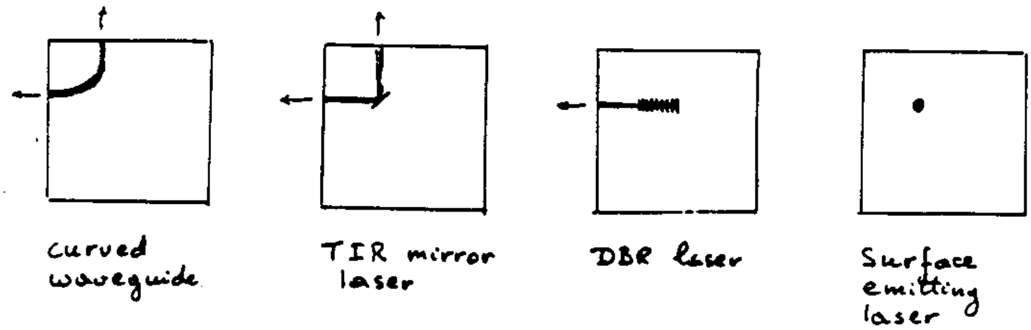
INTEGRATION OF LASER DIODES
THE CAVITY LENGTH PROBLEM

PROBLEM:



chip width = laser length

SOLUTIONS:

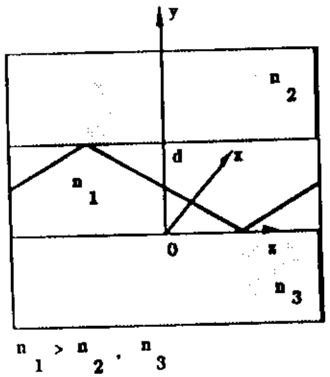


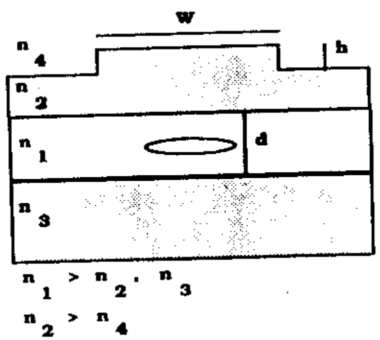
Building blocks

Optical components

Passive elements (waveguides, splitters,...)
III-V, Si, LiNbO3, glass, polymers,...

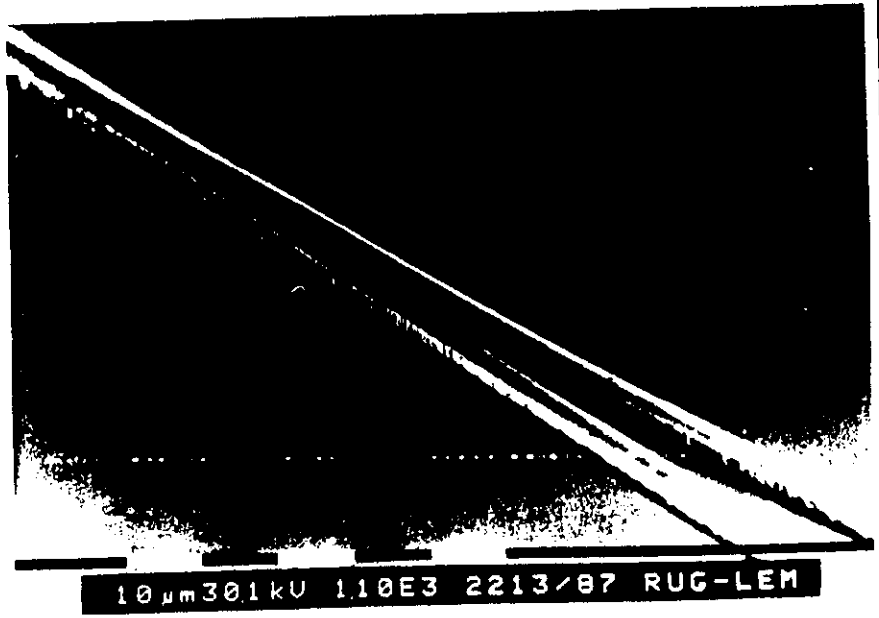
Active elements (switches, modulators,...)
III-V, LiNbO3, polymers,...





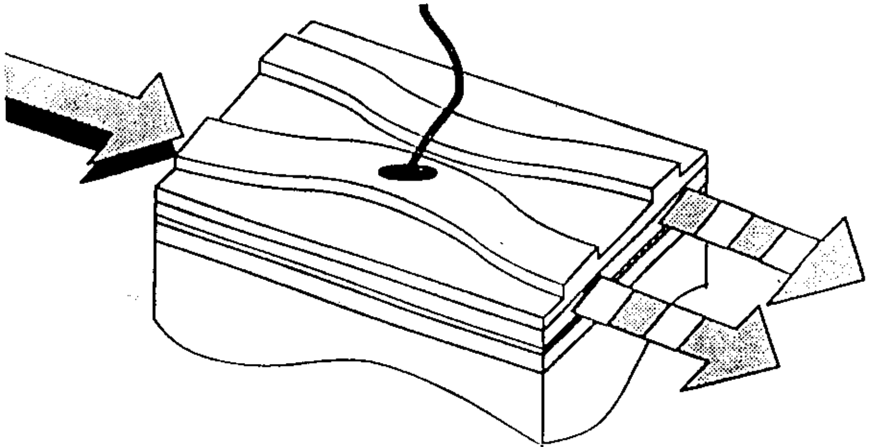
2 - Building blocks

RIE-etched waveguide



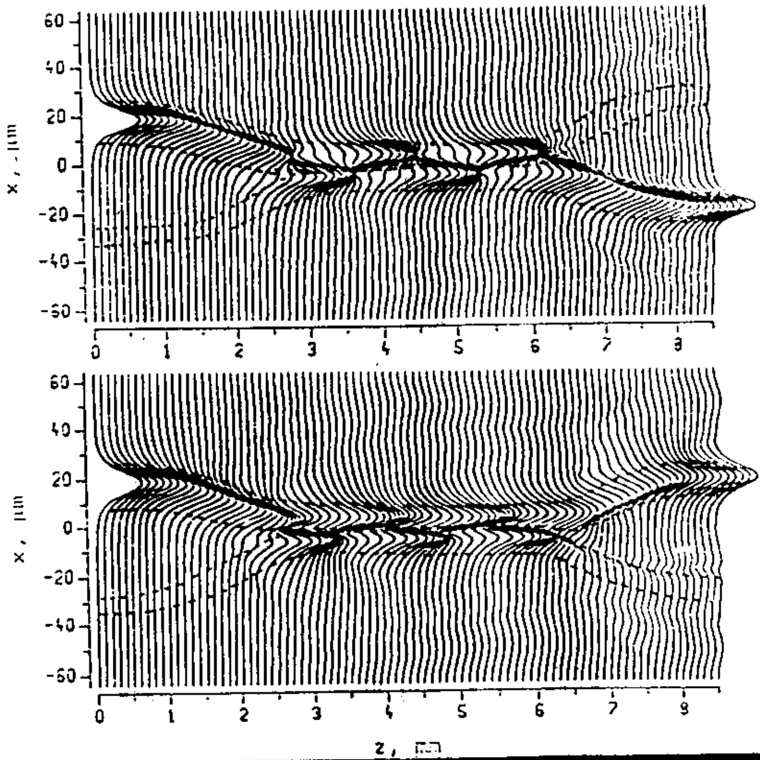
2 - Building blocks

Waveguides for integrated optics:
directional coupler



2 - Building blocks

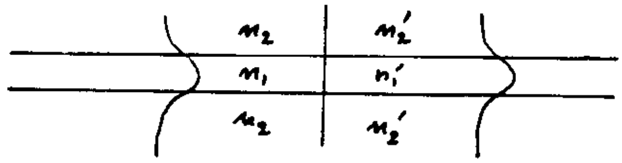
Waveguides for integrated optics:
directional coupler



COUPLING BETWEEN ACTIVE & PASSIVE WAVEGUIDES

laser passive — passive modulator — passive detector

Ideal coupling:

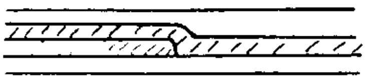


very difficult to make

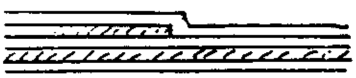
$n_1 - n_2 \approx n_1' - n_2'$ → mode matching

$n_1 - n_1'$ and $n_2 - n_2'$ small → little reflection (except if laser facet is needed)

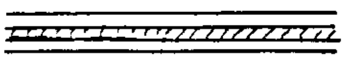
COUPLING BETWEEN ACTIVE AND PASSIVE WAVEGUIDES



Butt coupling



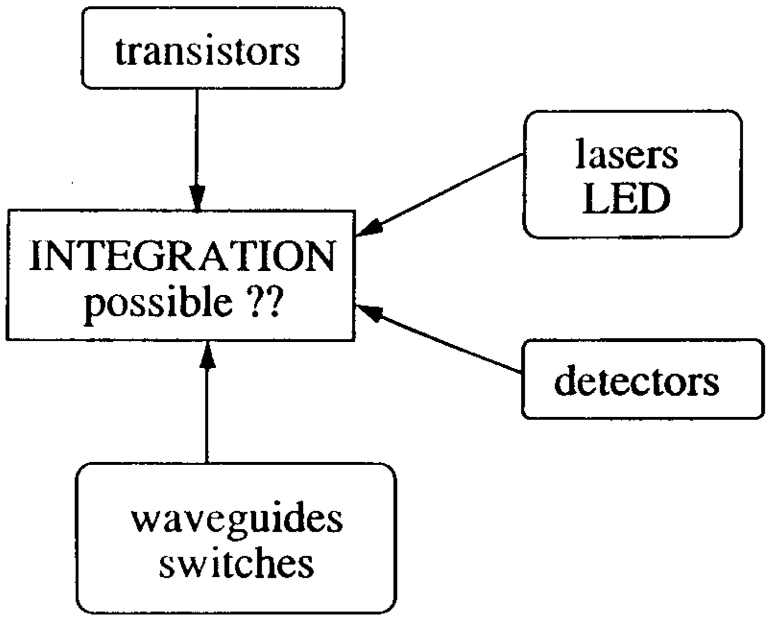
Evanescent field coupling (works very well for detectors)



Quantum well active device

- two growth steps
- growth interruption near active layer
- incompatibility between doping in active and passive region

Techniques



Techniques

Different techniques can be used:

* **hybrid integration**
* **monolithic integration**
    homo-epitaxial growth
    hetero-epitaxial growth

Alternatives:

* **flip-chip integration**
* **epi-lift-off**

Techniques

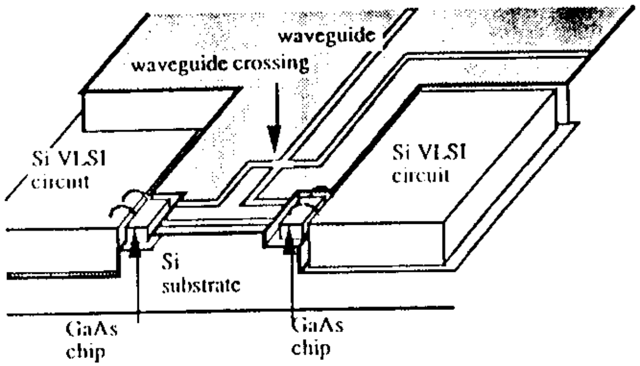
hybrid integration

Integration of different chips:

by means of epoxy / solder

on the same carrier

interconnections via wires



3 - Techniques

monolithic integration

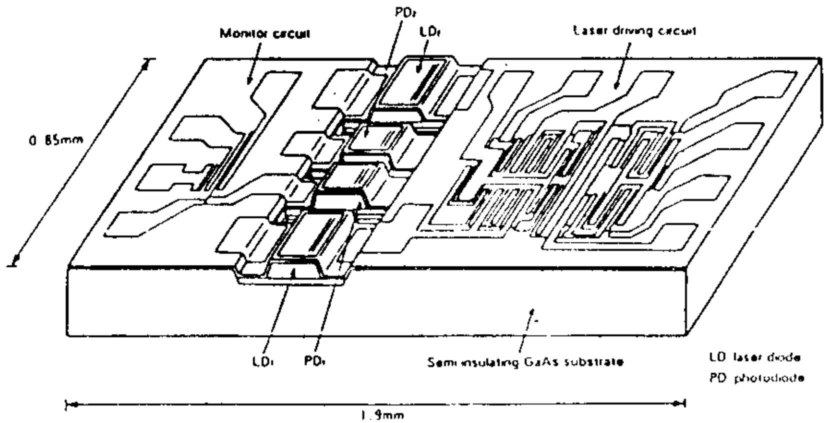
Integration of different chips:

via "crystalline" growth

on the same carrier

interconnections on chip-level

Structure of high speed modulation laser diode



Techniques

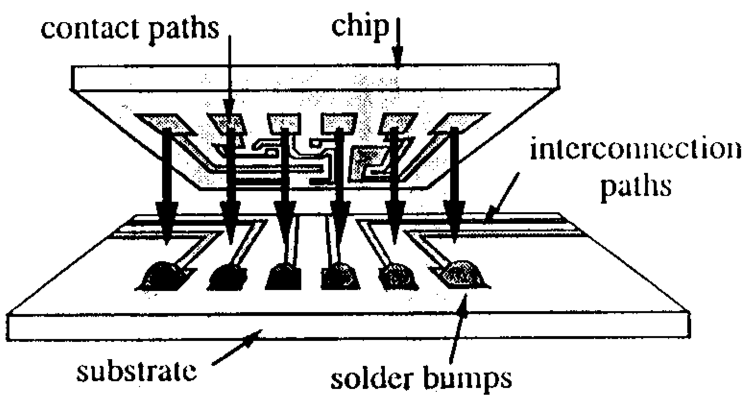
monolithic integration

problems:

* materials incompatibility
  (GaAs on Si, GaAs on InP,...)
* different layerstructures
  (Laser + waveguide,...)
* chip processing difficulty
* lasers are power hungry devices

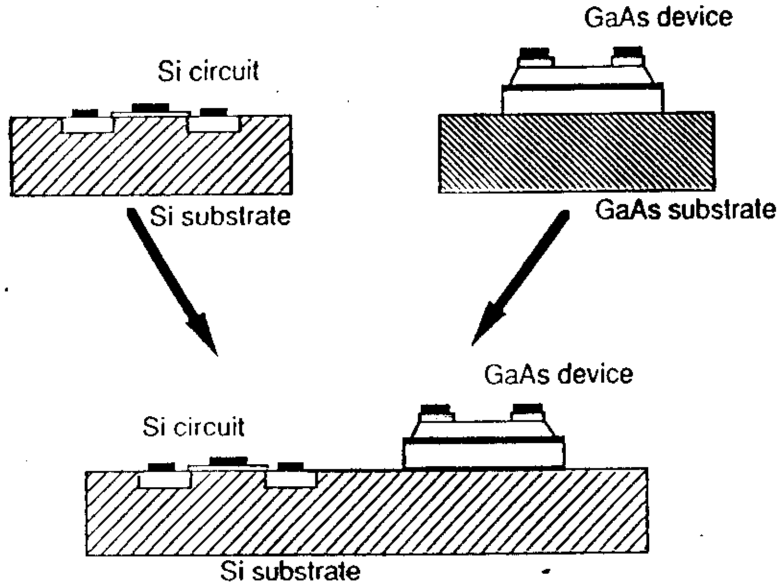
Techniques

flip-chip integration



Example

GaAs on Si integration



Advantages

- GaAs and Si devices optimized separatly
- final integration similar to monolithic integration (using heteroepitaxy)

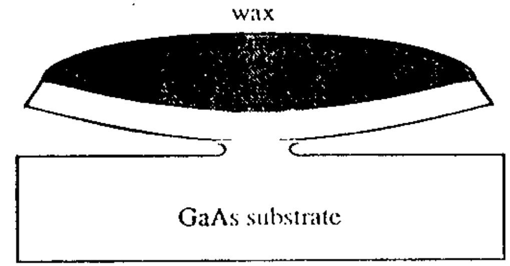
Problems

- very fragile ELO film (to be supported)
- alignement
- degradation

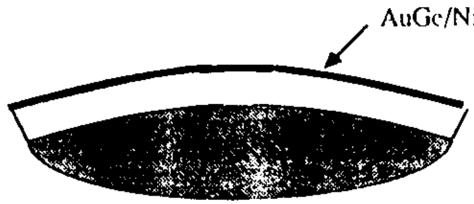
3. LED epi-lift-off

ELO strategy 2 using a wax carrier

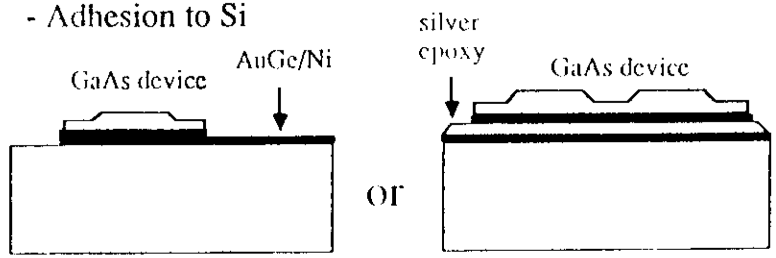
- ELO etch in HF:DI (1:5)



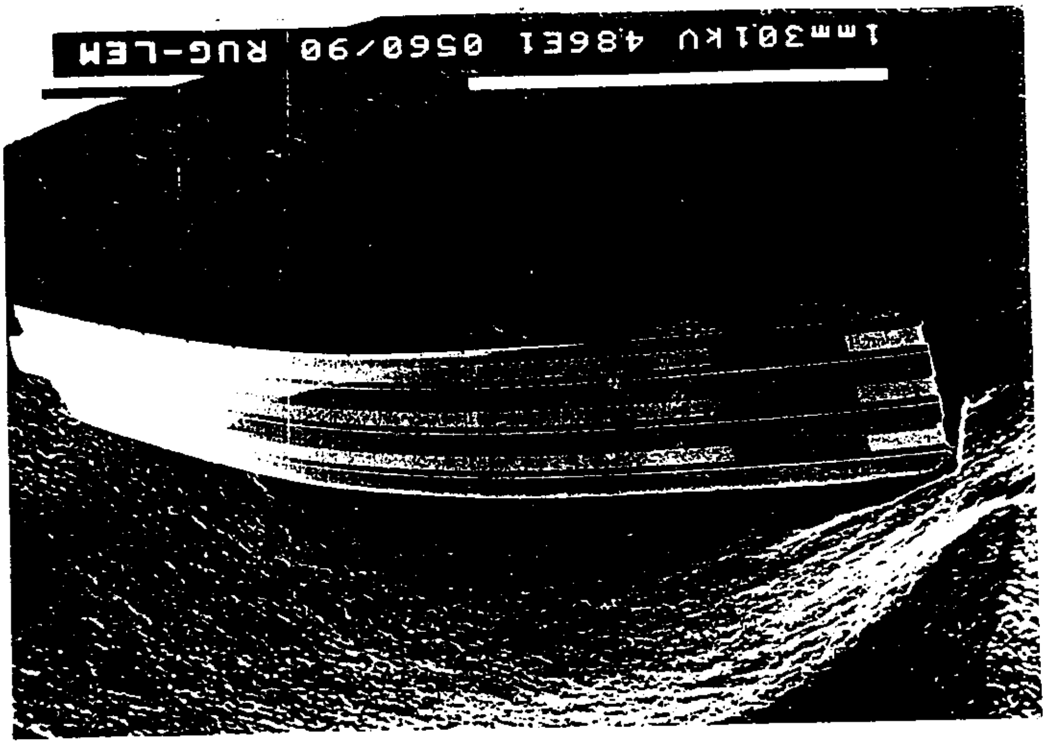
- Deposition of AuGe/Ni for backside contact

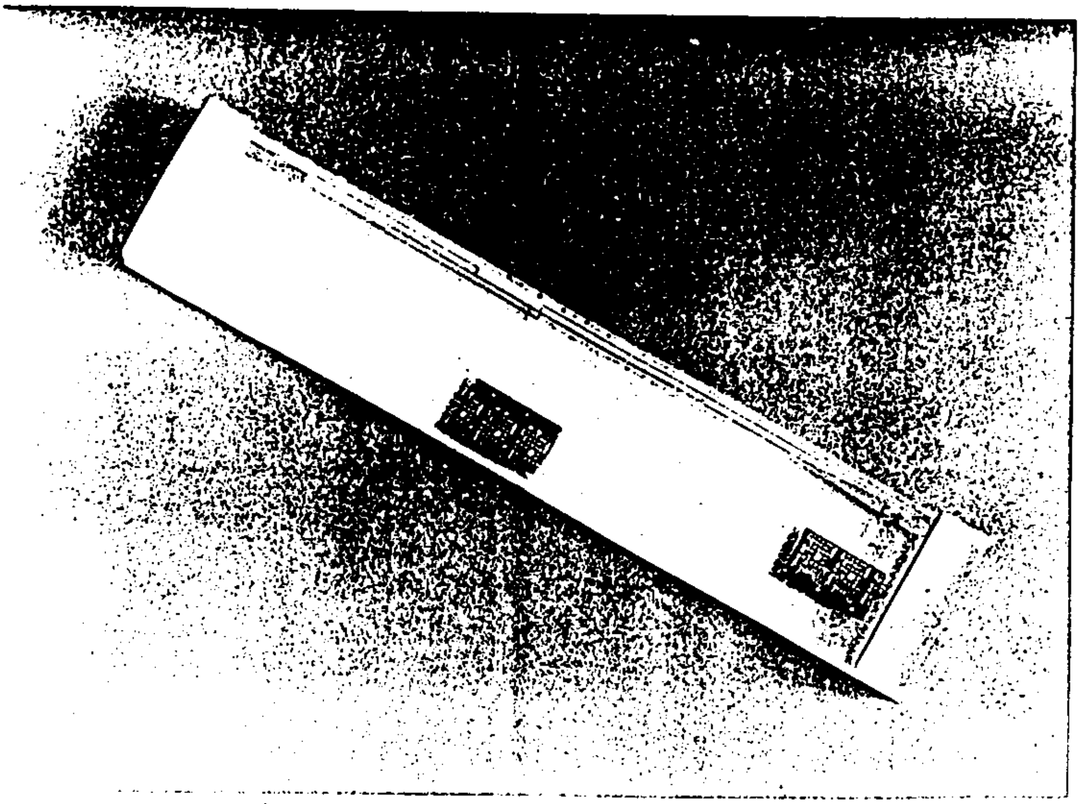


- Adhesion to Si



fast alloying at 450 °C with silver epoxy





Photograph of 1 x 2 lithium niobate optical switch
with epitaxial lift-off GaAs MESFET circuits

GEC-Marconi

Processing

Integration (monolithic, ELO,...):

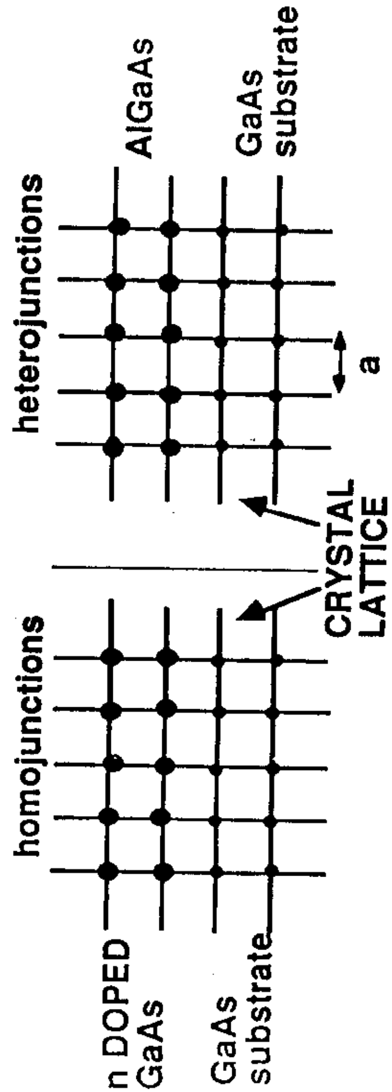
- * change design
- * change processes
  - epitaxial growth
  - lithography
  - metallisations
  - etching
  - ......

Problems can differ very much

creativity and flexibility required

EPITAXIAL GROWTH

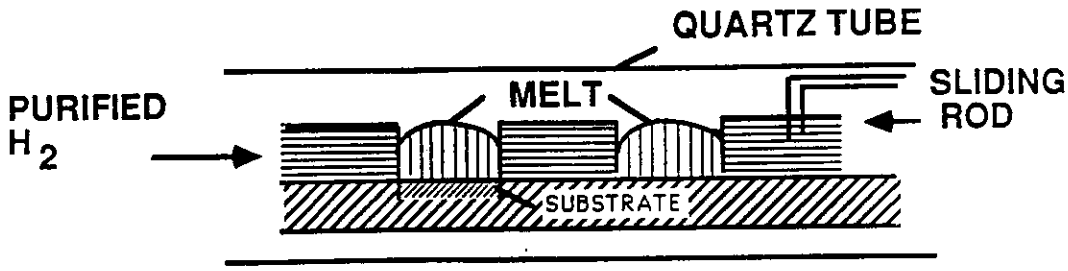
GROWTH OF MONOCRYSTALLINE MATERIAL ON SAME OR DIFFERENT CRYSTAL



REQUIREMENT : IDENTICAL LATTICE CONSTANT (a)

TECHNIQUES : LPE
(MO)CVD
MBE

LIQUID PHASE EPITAXY (LPE)

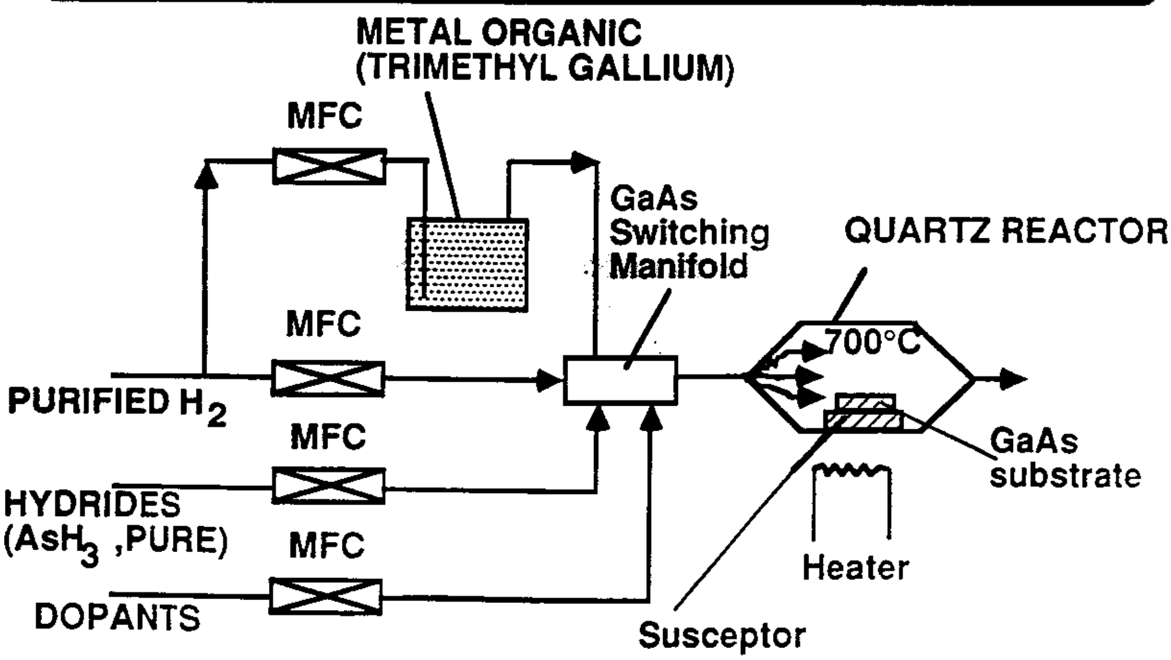


800°C, COOLING AT 1°C/MIN

MELT : In + Ga + As + P + (dopants)
SUBSTRATE : InP

- THERMODYNAMICAL EQUILIBRIUM PROCESS
- FABRICATION METHOD OF LASER DIODES
- THINNEST LAYER : 0.1 µm ; SMALL AREA

PRINCIPLE OF MOCVD REACTOR FOR EPITAXIAL GROWTH



(METAL ORGANIC) CHEMICAL VAPOR DEPOSITION (MO)CVD

EPITAXIAL GROWTH FROM THE VAPOR PHASE

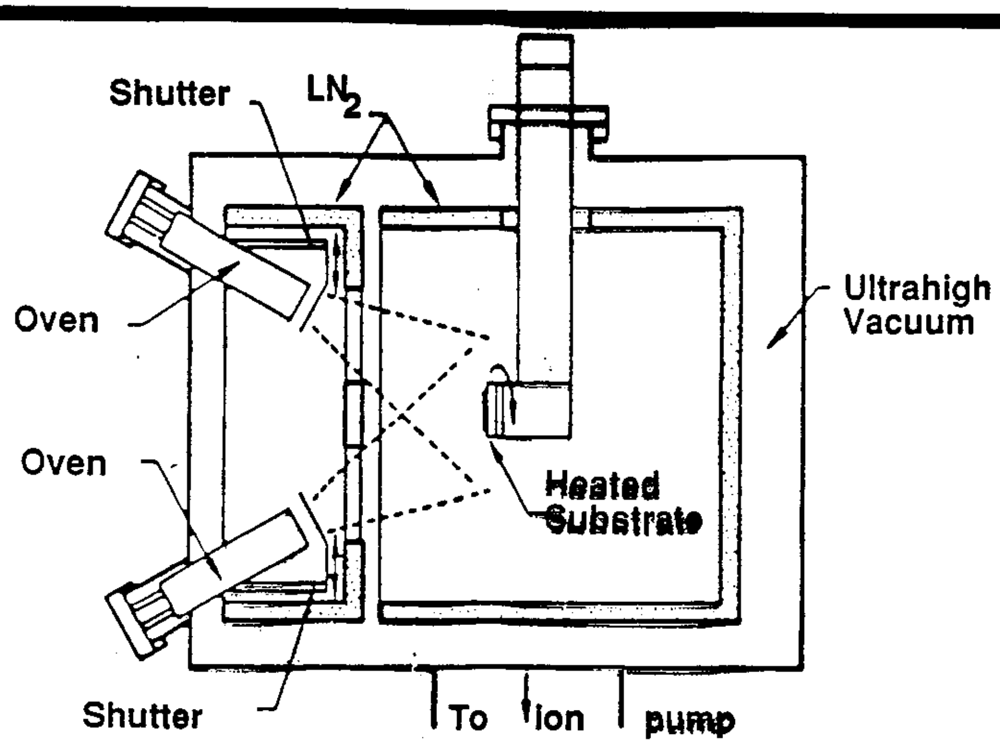
ADVANTAGES

- GROWTH OVER LARGE AREA
- VERY THIN LAYERS (10 - 100 Å) POSSIBLE
- SHARP INTERFACES

PROBLEM : <u>SAFETY</u>

- HIGHLY TOXIC ARSINE
- (PYROFORIC METALORGANICS)
- (EXPLOSIVE H_2)

MOLECULAR BEAM EPITAXY (MBE)



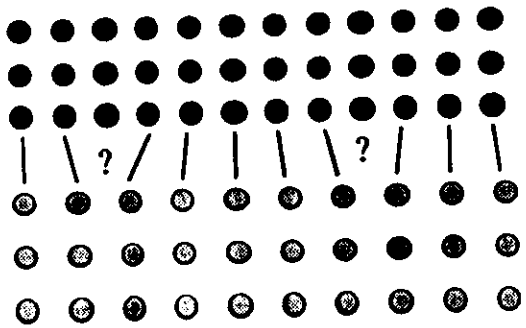
Processing

epitaxial growth

hetero-epitaxy:

≠ crystallographic structure

≠ thermal expansion



HETEROEPITAXY : GaAs on Si

WHAT :

EPITAXIAL GROWTH OF GaAs LAYERS ON SILICON SUBSTRATES

POTENTIAL APPLICATIONS :

- Monolithic integration of GaAs and Silicon devices with the goal of combining the sophistication of Si VLSI technology with the superior speed and/or optoelectronic capabilities of GaAs-based micro-electronics
- The use of Si as a substrate for GaAs epitaxial deposition (e.g. solar cells)

FIRST PUBLISHED REPORT IN 1983

GaAs on Si
PERFORMANCE / MATERIAL PROBLEMS

<u>GENERIC PROBLEMS OF HETEROEPITAXY</u>

LATTICE MISMATCH (4%)

SYMMETRY MISMATCH

THERMAL EXPANSION MISMATCH

COMPLETE REMOVAL OF NATIVE OXIDE FROM Si SURFACE

GaAs on Si
PERFORMANCE PROBLEMS

- MAJORITY-CARRIER DEVICES (MESFET, HEMT) :

  PERFORMANCES COMPARABLE TO DEVICES FABRICATED IN GaAs

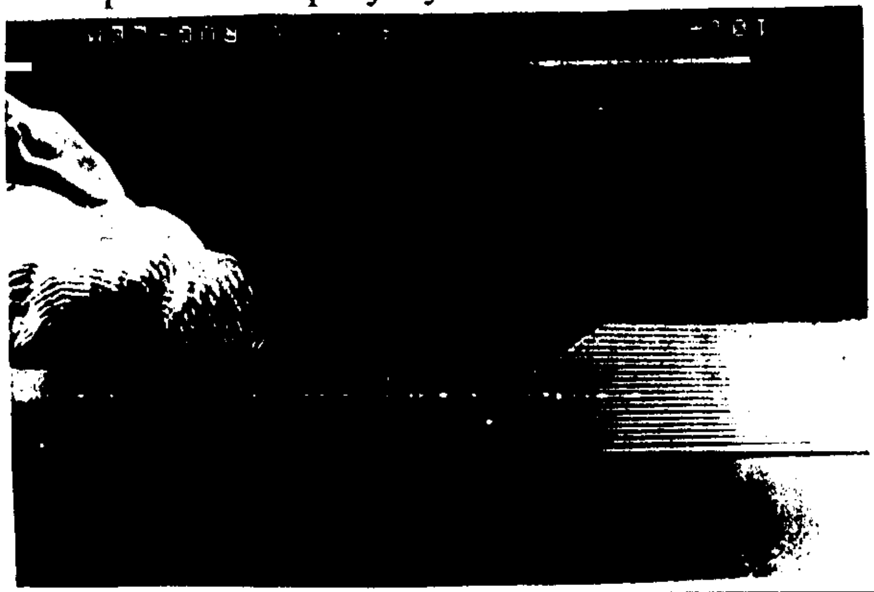
- MINORITY-CARRIER DEVICES (LED, LASER, ...) :

  CURRENTLY INFERIOR PERFORMANCE

4 - Processing

epitaxial growth

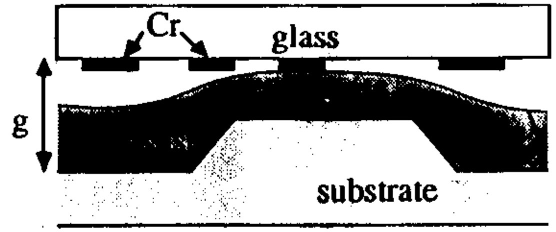
selective and/or non planar growth:
- formation of different crystallographic planes and polycrystalline material



Processing

lithografie

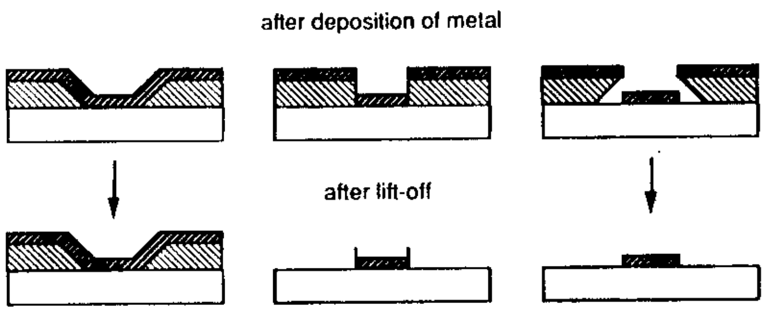
non-planarity results in problems for:
minimum feature size

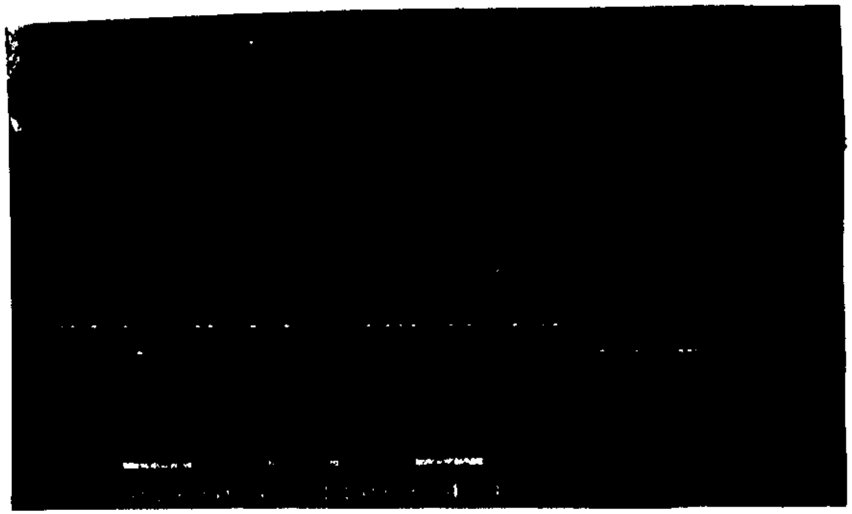


$$W = \sqrt{\lambda \cdot g}$$

4 - Processing

resist profile for lift off

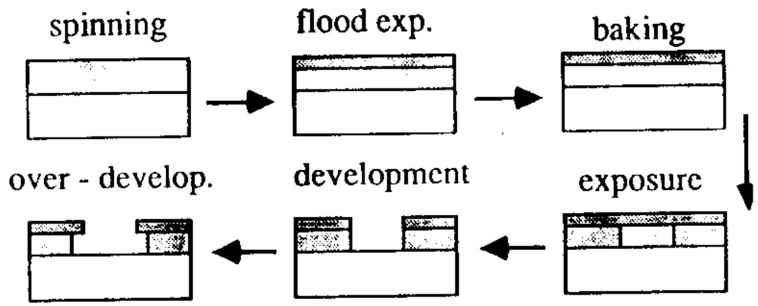




4 - Processing

lithografie

advanced resists and lithography: **NEPPOS**



Processing

metallisations

Different materials required:

ohmic contacts (Au, Ge, Ni, Zn, Ti, Pt, Pd, Ge, ...)

Schottky contacts (Ti, W, ...)

interconnection (Al, Au, ...)

extra (Cu, Ag, In,...)

all must be compatible:

with each other

with used materials

Processing

etching

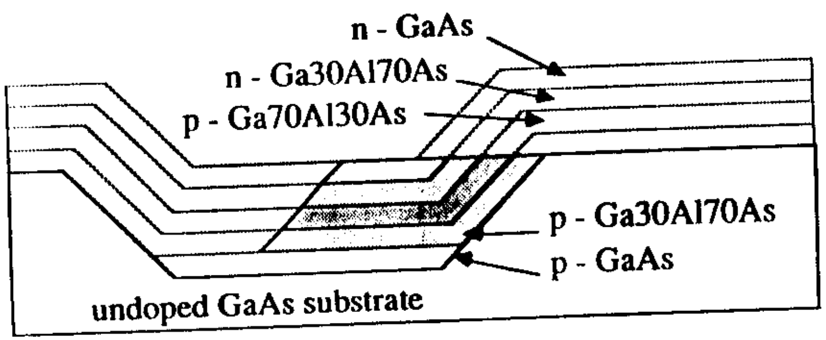
Different materials require:

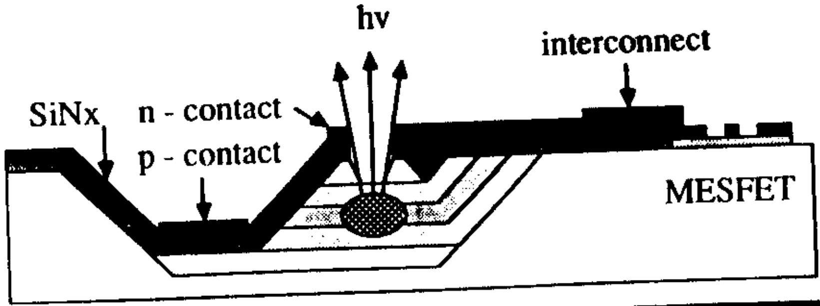
* variety on etchants (selective and non-selective)
* perfect control on etched profile (crystallographic orientation, layerstructure)

Processing

etching

influence of layerstructure
on etched profile





Processing

etching

Dry etching processes

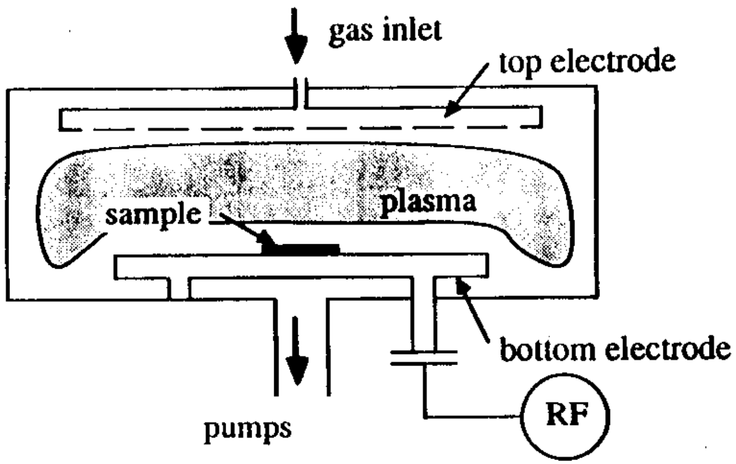
Several forms:
- Reactive Ion Etching (RIE)
- Reactive Ion Beam Etching (RIBE)
- Ion Beam Milling
- .....

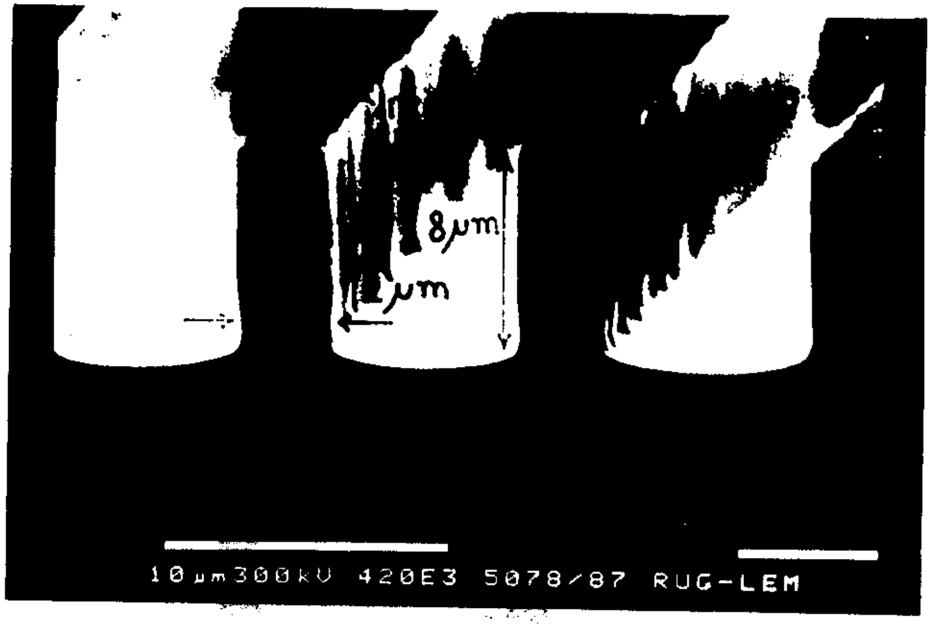
Ions hit surface with certain velocity
Combination of impact and chemical effect

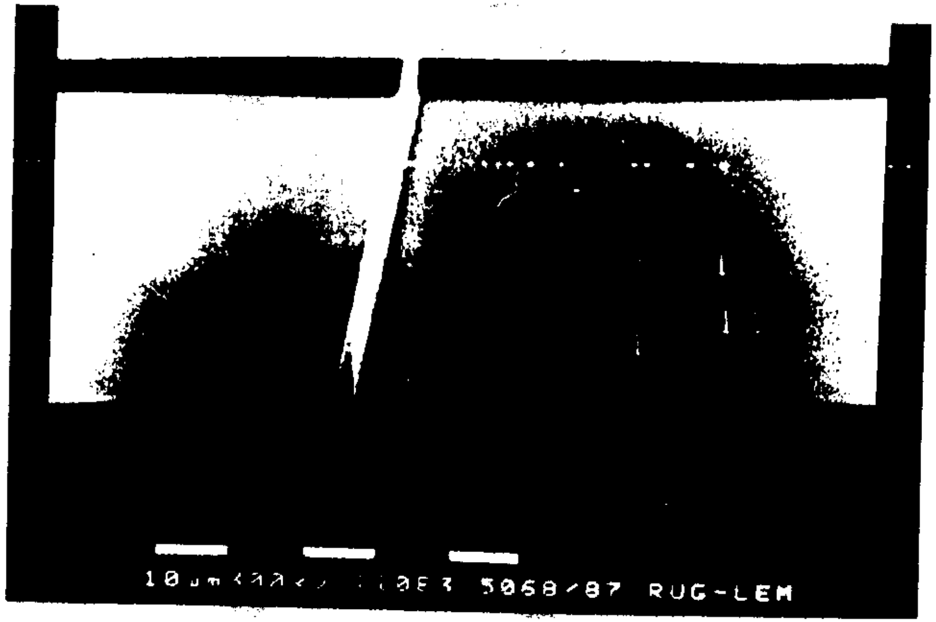
+ strongly anisotropic etching possible
+ independent etching of different materials
- damage effects
- low selectivity

Processing

Reactive Ion Etching



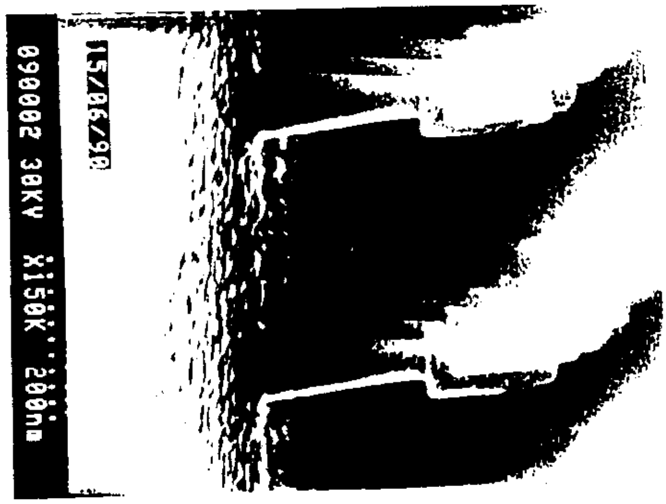




4 - Processing

LEA

Reactive Ion Etching of quantum dots



(Glasgow University)

MATERIAL COMBINATIONS

OEIC

E device(s)	Electronics	# reports	techniques	examples
Al)GaAs	(Al)GaAs	+	monolithic	receivers, laser drivers
InP	InP	+	monolithic	" "
Si - detector	Si	++	monolithic	CCD
- modulator	Si	-	monolithic	
- emitter	Si	-	monolithic	
InP	GaAs	+/-	het. epit / ELO	receivers, laser drivers
Al)GaAs	Si	+/-	het. epit. / ELO	laser or modulator driver
InP	Si	-	het. epit. / ELO	" "
iNbO3, ...	GaAs	-	ELO	+ receiver switch driver
lass	amorphous Si II - VI	++	CVD	active matrix LCD

MATERIAL COMBINATIONS PIC

Active OE device	Passive waveguide	# reports	techniques
InP	InP	+	monolithic
GaAs	GaAs	+	monolithic
GaAs or InP	polymeric waveguide	-	spun-on film
GaAs or InP	glass	-	hybrid / ELO

Examples

LEA

receiver:
- * general performances
- * photoreceiver via flip-chip

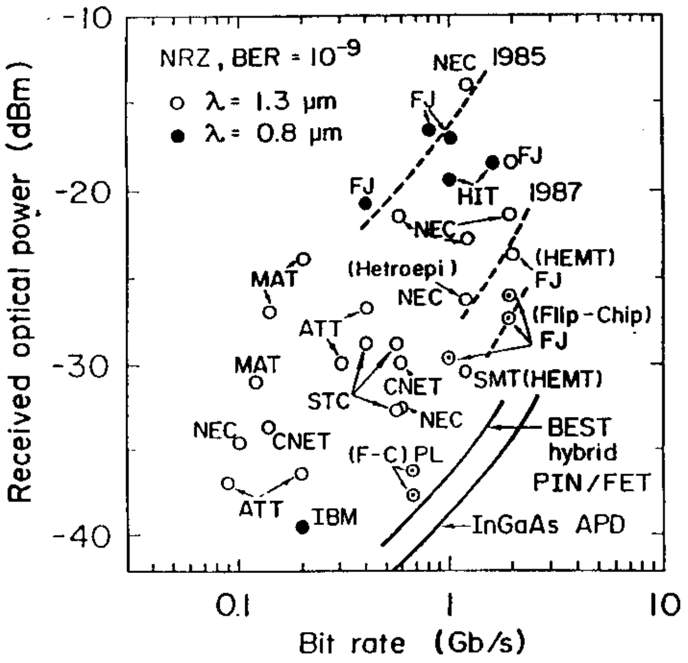
source:
- * Laser - waveguide
- * GaAs on InP transmitter

systems:
- * IBM optoelectronic link
- * optically coupled 3D memory

5 - Examples

receiver:

* general performances

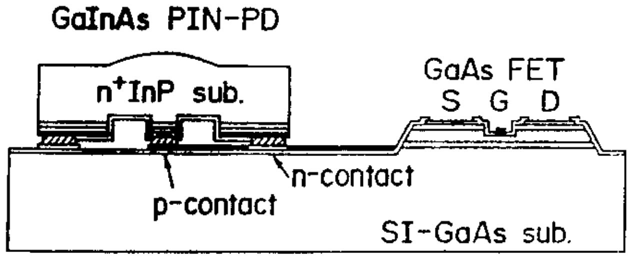


5 - Examples

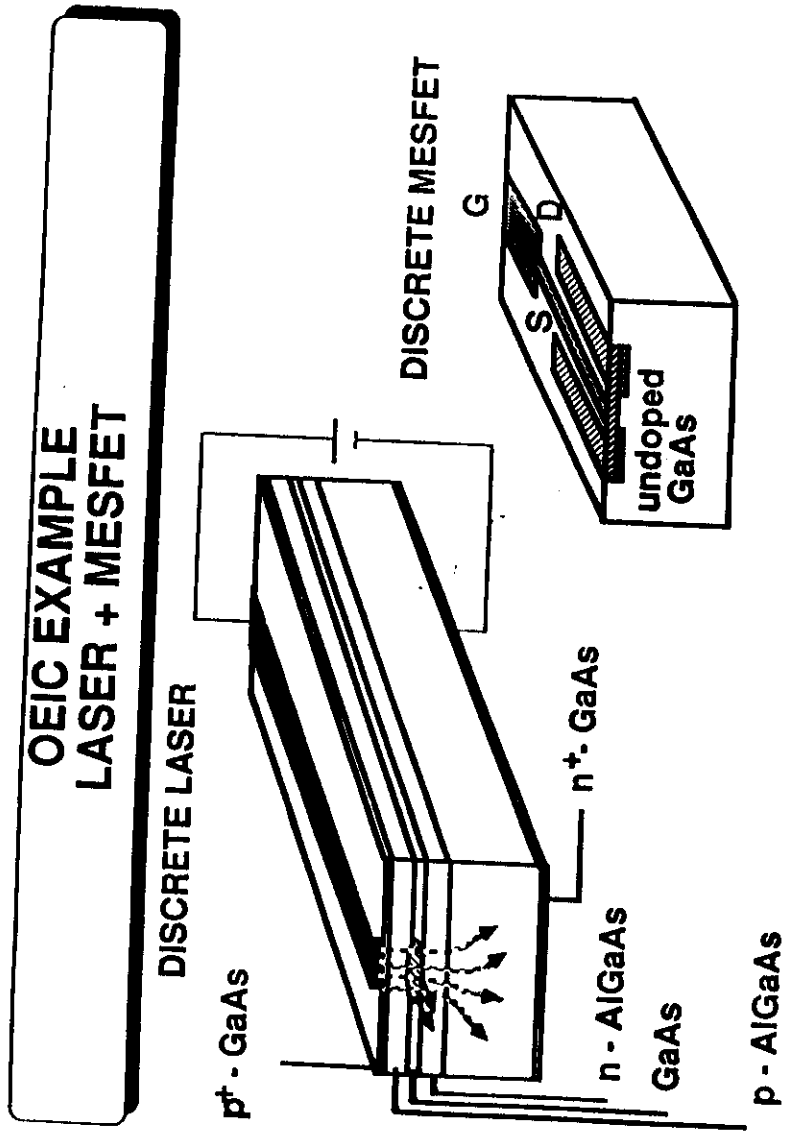
receiver:

* photoreceiver via flip-chip

GaInAs PIN/GaAs amplifier receiver



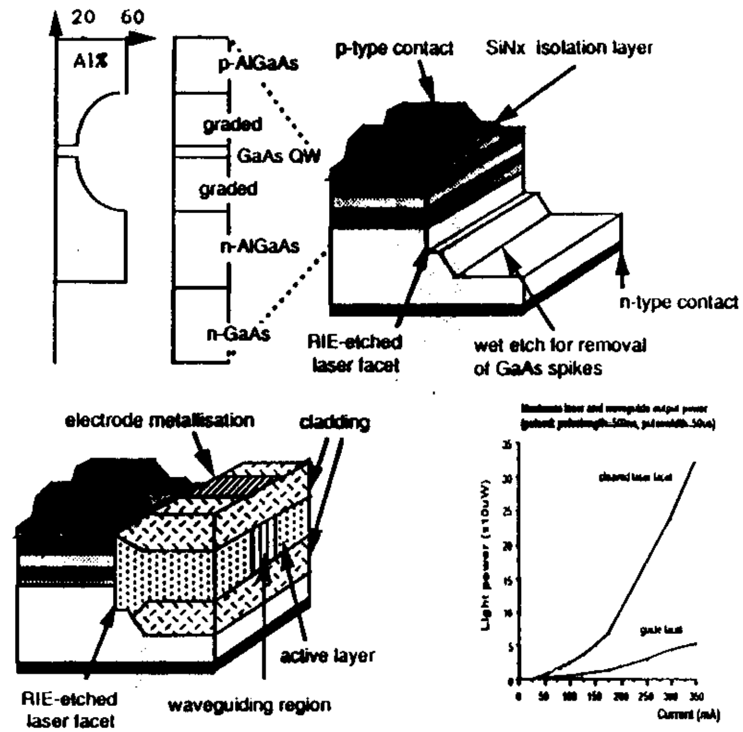
Makiuchi et al. (Fujitsu), Electr. Let. vol 24 No 16



Examples

source:

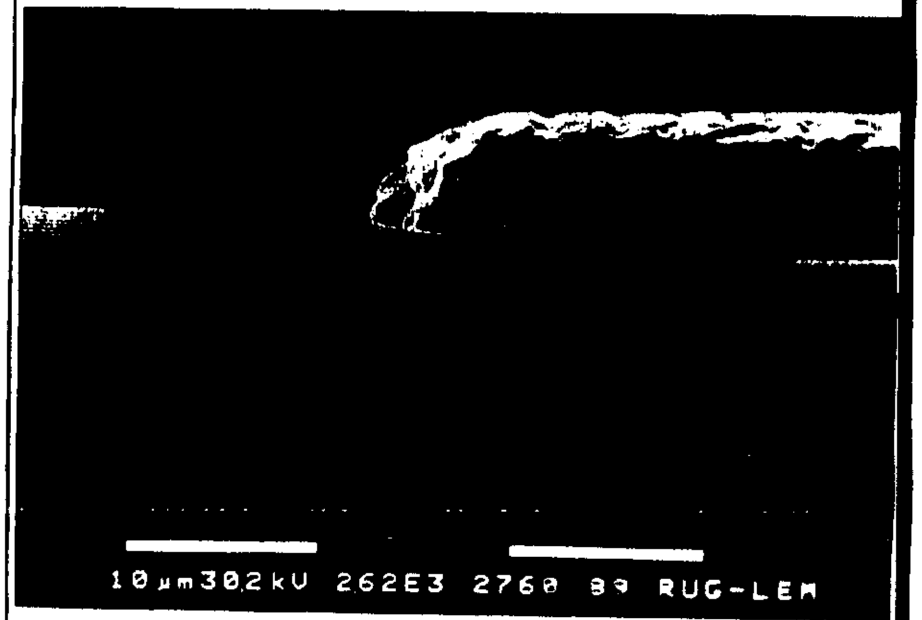
* Laser (GaAs) - waveguide (polymers)



5 - Examples

source:

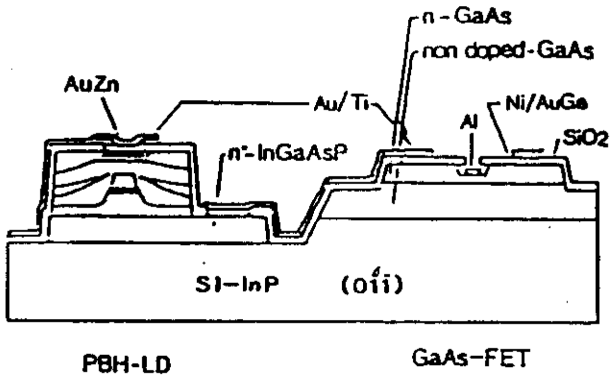
* Laser - waveguide (III-V)



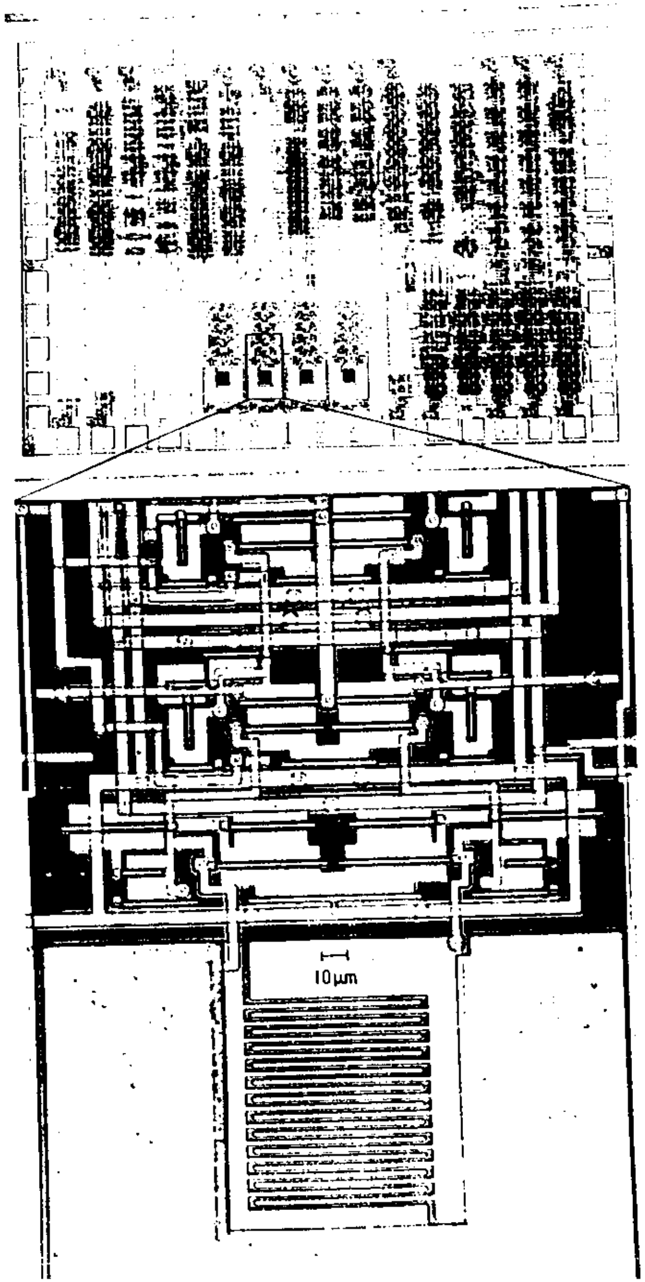
5 - Examples

source:

* GaAs on InP transmitter



Suzuki et al., Techn Dig. ECOC'88



Conclusions

INTEGRATION OF OPTOELECTRONIC COMPONENTS

necessary for:
- keeping high performances of individual components in complete systems
- reduce power consumption
- eliminate sensitivity to environment
- increased functionality

slowed down by:
- huge problems during fabrication

but:
- feasability is proven
- high expectations (performance, cost,..)

MODELLING AND DESIGN

OF

INTEGRATED OPTIC CIRCUITS

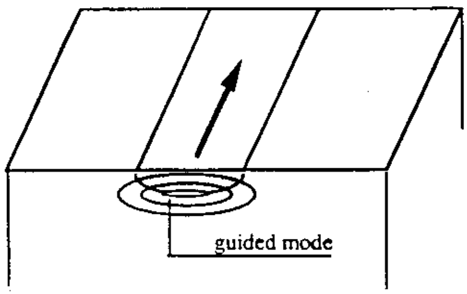
Outline

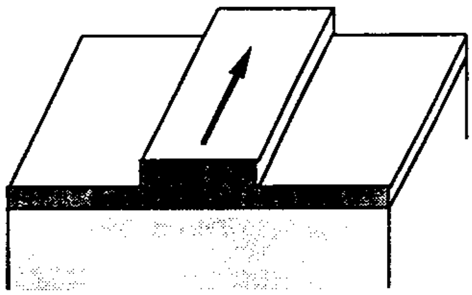
- INTRODUCTION
- 2D MODE SOLVERS
  - OPTICAL WAVEGUIDE MODES : DEFINITIONS
  - EFFECTIVE INDEX METHOD
  - SCALAR FINITE DIFFERENCE METHOD
  - VECTORIAL FINITE DIFFERENCE METHOD
- BEAM PROPAGATION METHOD
- TRANSFER MATRIX METHOD
- COUPLED MODE THEORY

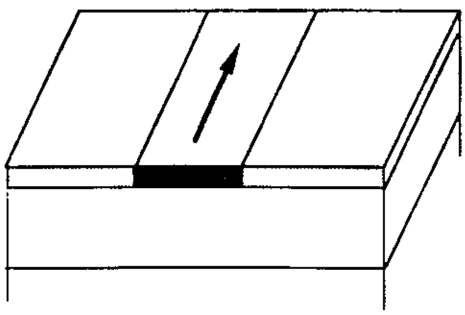
Basic IOC's Components :

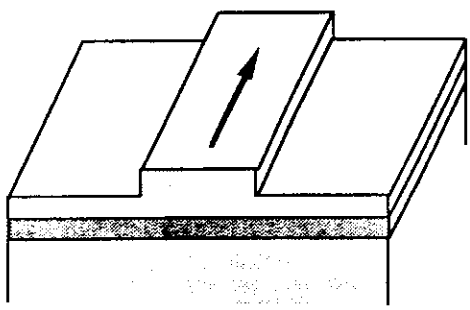
- Passive
  - waveguides
  - bends
  - Y-junctions
  - crossings
  - directional couplers
  - structures with gratings
- Electrooptic
  - phase and intensity modulators
  - space switches

Basic IOC's Components : waveguides

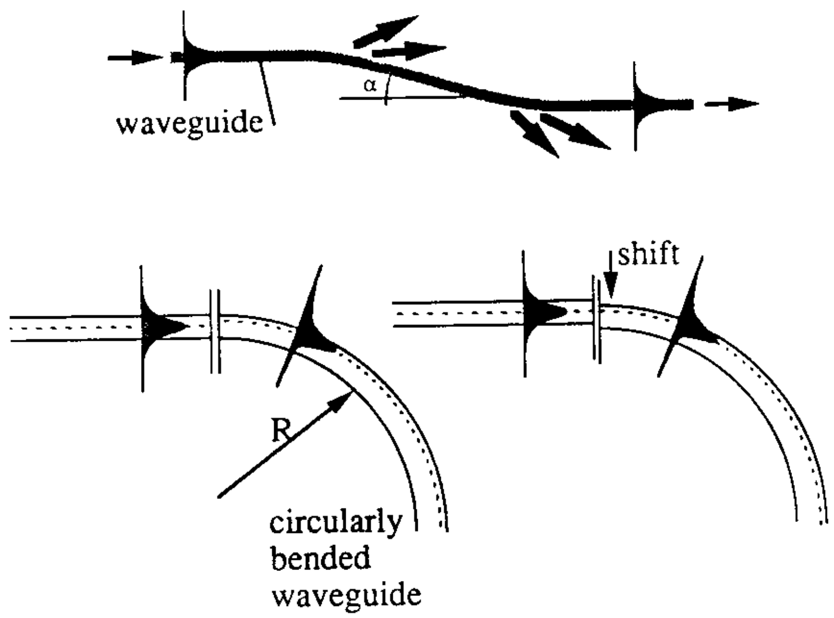




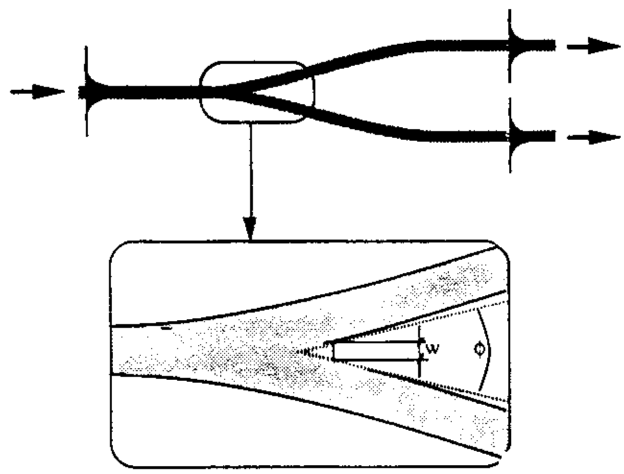




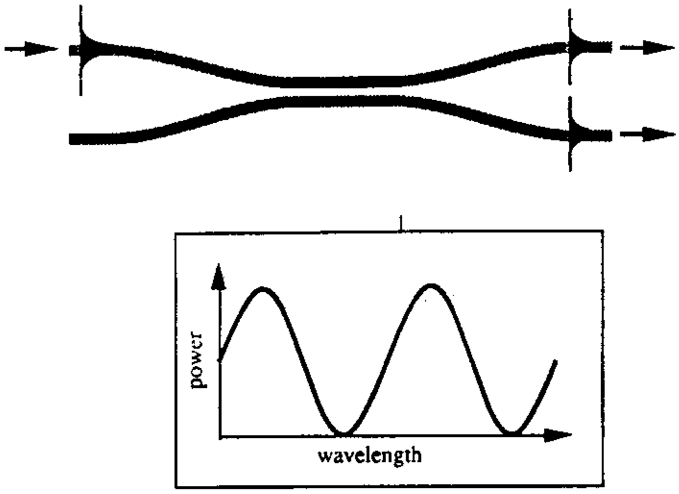
Basic IOC's Components : bends



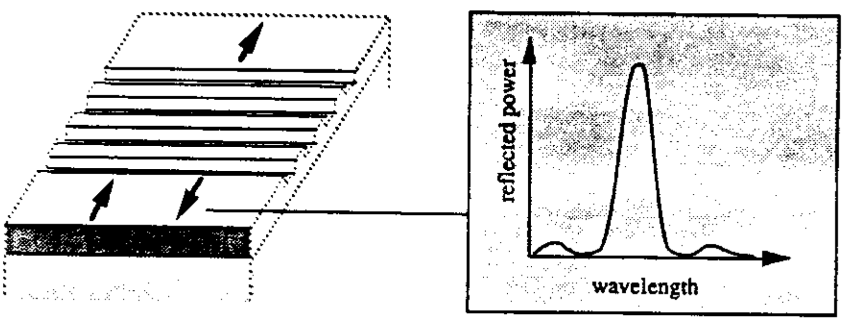
Basic IOC's Components : Y-junctions



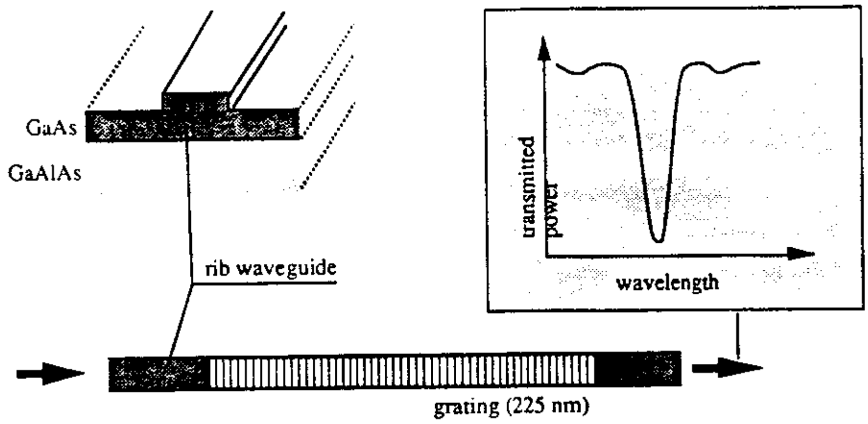
Basic IOC's Components : Directional couplers



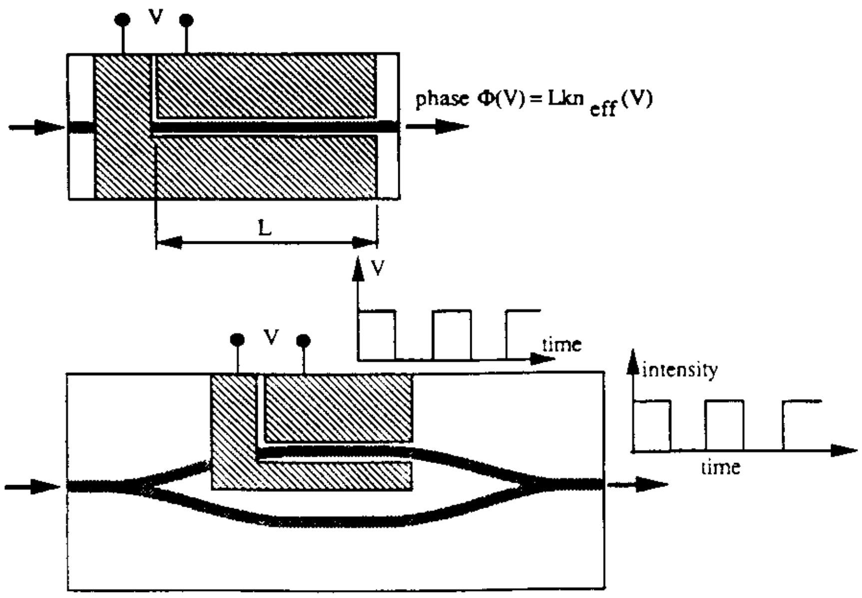
Basic IOC's Components : gratings (1)



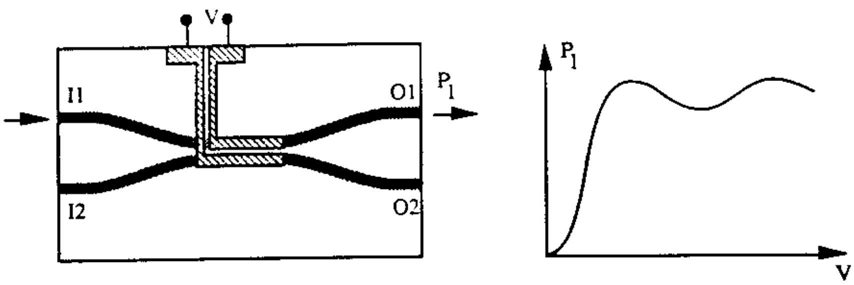
Basic IOC's Components : Gratings (2)

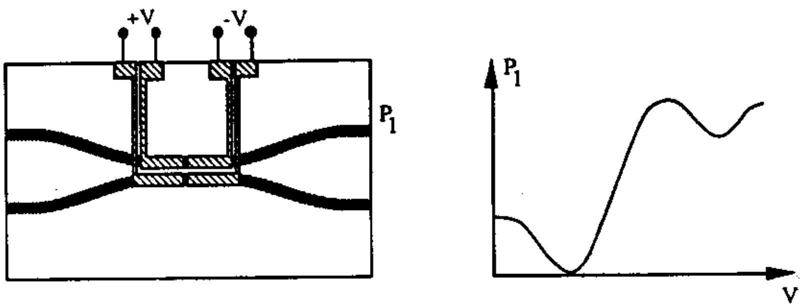


Basic IOC's Components Electrooptic phase and intensity modulators



Basic IOC's Components
Electrooptic space switches





Optical Waveguide Modes : definitions

Maxwell's equations

[time-dependence : exp (jωt)]

$\vec{\nabla} \times \vec{E} = -j\omega\mu_0 H$

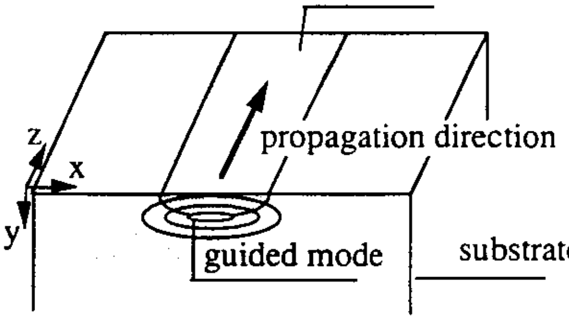
$\vec{\nabla} \times \vec{H} = j\omega\varepsilon_0\varepsilon_r\vec{E}$

$\vec{\nabla} \cdot (\varepsilon_r \vec{E}) = 0$

$\vec{\nabla} \cdot \vec{H} = 0$

+ continuity conditions for $\vec{E}, \vec{H}$

+ radiation condition at ∞



Optical Waveguide Modes : definitions

$$\nabla^2 \vec{H} + \frac{\vec{\nabla}\varepsilon_r}{\varepsilon_r} \times (\vec{\nabla} \times \vec{H}) + k_0^2 \varepsilon_r \vec{H} = 0$$

$$\nabla^2 \vec{E} + \vec{\nabla}\left(\frac{\vec{\nabla}\varepsilon_r}{\varepsilon_r} \vec{E}\right) + k_0^2 \varepsilon_r \vec{E} = 0$$

$$k_0^2 = \omega^2 \varepsilon_0 \mu_0$$

→ modal field representation

$$\vec{H}(x, y, z) = \vec{h}(x, y) \exp(-j\beta z) = (\vec{h}_t + \vec{h}_z) \exp(-j\beta z)$$

$$\vec{E}(x, y, z) = \vec{e}(x, y) \exp(-j\beta z) = (\vec{e}_t + \vec{e}_z) \exp(-j\beta z)$$

→ $\vec{e}_t$, $\vec{h}_t$ – transversal components

→ $\vec{e}_z$, $\vec{h}_z$ – longitudinal components

→ β – real propagation constant

Optical Waveguide Modes : definitions

Transversal components → complete vectorial field

either :

$$\vec{e}_t : \nabla_t^2 \vec{e}_t + (k_0^2 \varepsilon_r - \beta^2) \vec{e}_t = - \vec{\nabla}_t \left(\frac{\vec{\nabla}_t \varepsilon_r}{\varepsilon_r} \cdot \vec{e}_t \right)$$

→ $\vec{e}_z$, $\vec{h}_z$ and $\vec{h}_t$ can be computed from $\vec{e}_t$

or :

$$\vec{h}_t : \nabla_t^2 \vec{h}_t + (k_0^2 \varepsilon_r - \beta^2) \vec{h}_t = - \frac{\vec{\nabla}_t \varepsilon_r}{\varepsilon_r} \times (\vec{\nabla}_t \times \vec{h}_t)$$

→ $\vec{e}_z$, $\vec{h}_z$ and $\vec{e}_t$ can be computed from $\vec{h}_t$

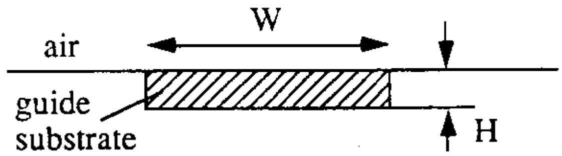
+ boundary conditions for $\vec{E}$, $\vec{H}$

+ conditions at ∞

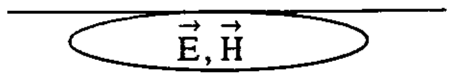
Optical Waveguide Modes : definitions

Simplification of vectorial modes ⟶ scalar approximation

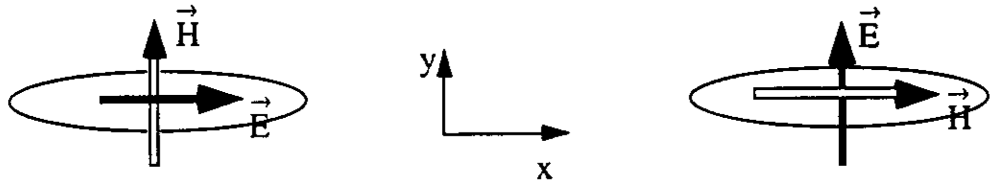
- Typical planar waveguide :
  - width W > height H
  - lateral index change small



⟶ vectorial modes



scalar modes



quasi - TE

$(|\vec{E}_x|, |\vec{H}_y|) >> (|\vec{E}_y|, |\vec{E}_z|, |\vec{H}_x|)$

quasi - TM

$(|\vec{H}_x|, |\vec{E}_y|) >> (|\vec{H}_y|, |\vec{H}_z|, |\vec{E}_x|)$

Optical Waveguide Modes : definitions

Example : equations for quasi - TE mode

$\vec{E}_y = 0$

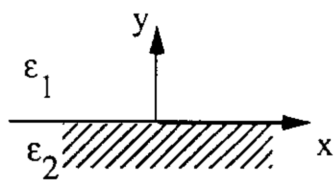
$\rightarrow \nabla_t^2 e_x + (k_0^2 \varepsilon_r - \beta^2) e_x = 0$

* $e_x = \phi$ (a scalar function)
* (e_z, h_x, h_y, h_z) can be computed
* small lateral index variations :

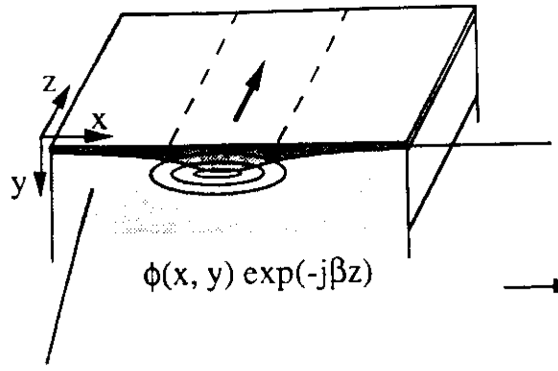
$\rightarrow e_z \approx 0, \; h_x \approx 0, \; h_y \approx \frac{\beta}{\omega\mu_0} e_x$

$\rightarrow$ + boundary conditions

TE : e_x and $\frac{\partial e_x}{\partial y}$ continuous



Effective Index Method : theory



$\phi(x, y)\exp(-j\beta z)$

$n(x, y) = n_0(y) + \Delta n(x, y)$

→ <u>modal field - scalar approximation</u>

$$\nabla_t^2\phi + [k^2 n^2(x,y) - \beta^2]\phi = 0$$

$\phi(x, y) = ?\quad \beta = ?$

→ <u>assumption</u>

$\phi(x, y) = F(x, y)\,.\,G(x)$

where fast variations of ϕ along x are taken up in $G(x)$

$$\rightarrow \frac{\partial F(x,y)}{\partial x} \approx 0$$

Effective Index Method : Theory

Eq(*) → $$\frac{1}{G}\frac{d^2G}{dx^2} + \frac{1}{F}\frac{\partial^2 F}{\partial y^2} + (k^2n^2 - \beta^2) = 0$$

function of x   function of x, y

→
$$\frac{1}{F}\frac{\partial^2 F}{\partial y^2} + n^2k^2 = \gamma^2(x)$$
$$\frac{1}{G}\frac{d^2G}{dx^2} - \beta^2 = -\gamma^2(x)$$

$\gamma = kn_{eff}$

→ $$\frac{\partial^2 F}{\partial y^2} + [k^2n^2 - k^2n_{eff}^2(x)]\,F = 0 \rightarrow F(x, y),\ n_{eff}(x)$$
1d wave equation (to be solved for each x)

→ $$\frac{d^2G}{dx^2} + [k^2n_{eff}^2(x) - \beta^2]\,G = 0 \rightarrow G(x), \beta$$
1d wave equation to be solved once

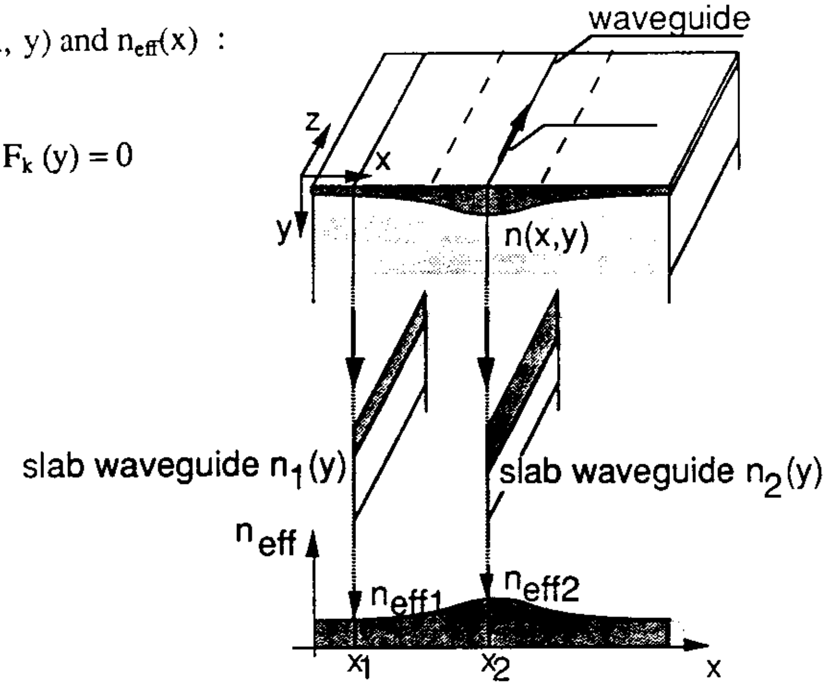
- This finally yields $\phi(x, y) = F, G$, and β.

Effective Index Method : Theory

- discretized solution for F(x, y) and $n_{eff}(x)$:

$$\frac{d^2F_k(y)}{dy^2} + k^2\,(n_k^2\,(y) - n_{eff(k)}^2)\,F_k\,(y) = 0$$

$$\phi(x_k,\ y) = F_k(y)\ .\ G(x_k)$$



Effective Index Method : Example

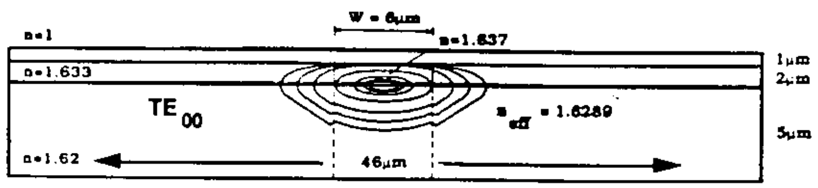
- channel waveguide in polymers

  λ = 845 nm

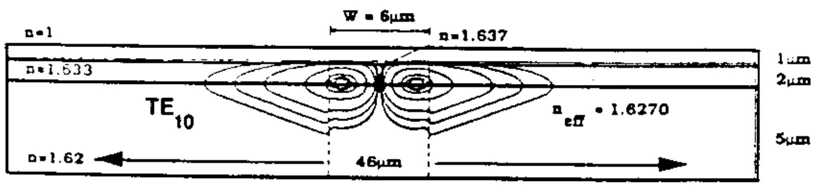
  contour plots of $|\phi(x, y)|$

  (0.05, 0.1, 0.2, 0.5, 0.8, 0.90, 0.95)

  ⟶ note rapid transitions of $|\phi(x, y)|$



Effective Index Method



Effective Index Method

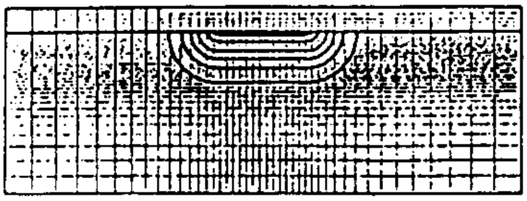
Scalar Finite Difference Method

BASIC EQUATION :

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + (k_0^2 \varepsilon_r - \beta^2) = 0 \qquad (1)$$

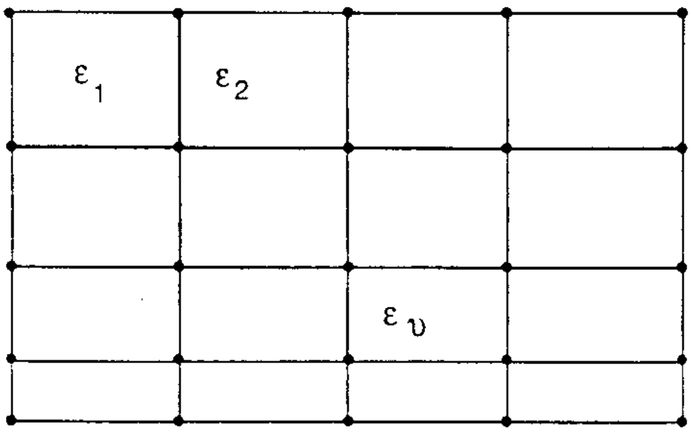
* A finite cross section is defined by enclosing the guide in a rectangular box, where $\phi = 0$ on the side walls

* In this box a graded **mesh** is defined



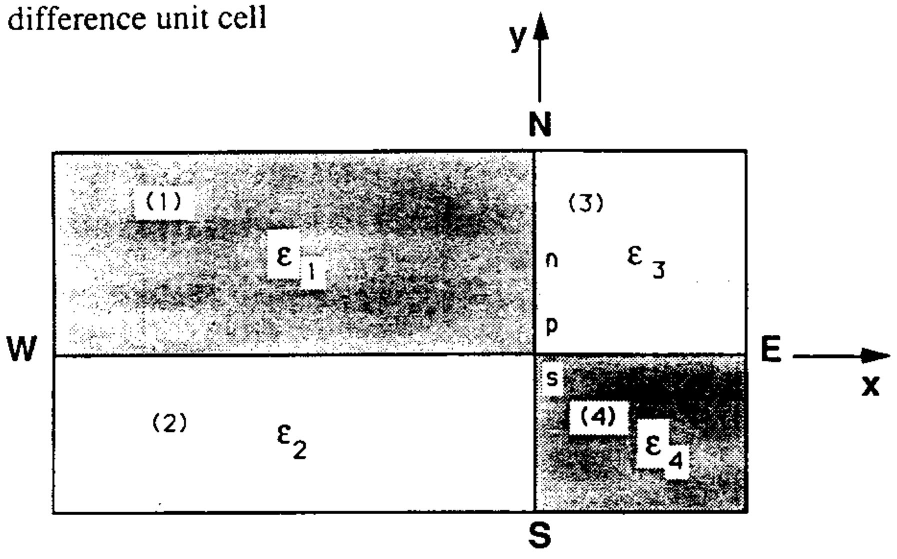
Scalar Finite Difference Method

* In each cell of the mesh the relative permittivity is assumed to be constant. Equation (1) applies in each subregion S_υ , with $\varepsilon_r = \varepsilon_\upsilon$.



Scalar Finite Difference Method

* Finite difference unit cell



Scalar Finite Difference Method

Continuity conditions :

$\left.\begin{matrix}\phi \\ \dfrac{\partial\phi}{\partial n}\end{matrix}\right\}$ continous at boundary between S_υ

Substitution of the discreted form of $\nabla_t^2\phi$ and the continuity conditions into (1) leads to :

$$\frac{2}{w(e+w)}\phi_W + \frac{2}{s(n+s)}\phi_S - \left(\frac{2}{w(e+w)} + \frac{2}{e(e+w)} + \frac{2}{s(n+s)} + \frac{2}{n(n+s)}\right)\phi_P + \frac{2}{e(e+w)}\phi_E + \frac{2}{n(n+s)}\phi_N \qquad (2)$$

$$+ k_0^2\,\frac{wn\varepsilon_1 + ws\varepsilon_2 + es\varepsilon_3 + en\varepsilon_4}{(e+w)\,(n+s)}\,\phi_P - \beta^2\phi_P = 0$$

Scalar Finite Difference Method

Equation (2) holds for each node point P. The resultant eigenvalue equation is of the form

$$[[A] - \beta^2 [U]]\ [X] = 0$$

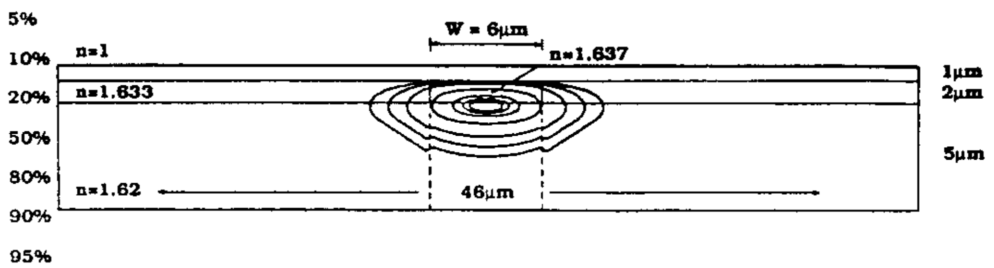
with

$$[X] = [\phi_1, \phi_2, \ldots, \phi_{NTOT}]^T$$

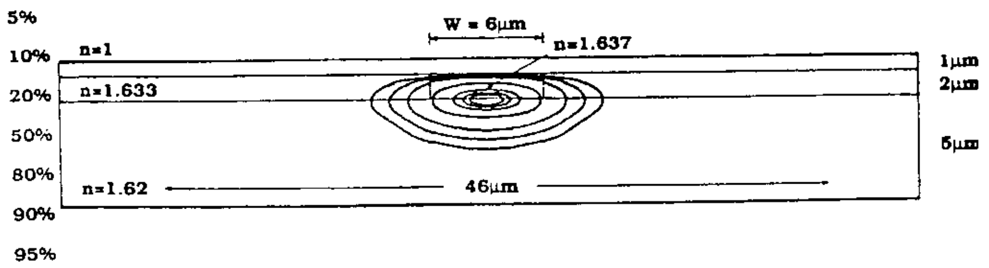
[U] is the unit matrix, and NTOT is the total number of mesh points. The matrix [A] is a real, but generally not symmetric, sparse matrix. Eigenvalues and corresponding eigenvectors of [A] are found by a simultaneous iteration algorithm.

Scalar Finite Difference Method

EFFECTIVE INDEX METHOD

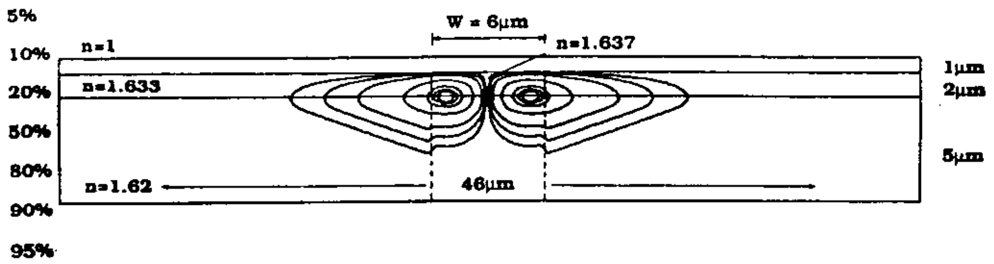


FINITE DIFFERENCE METHOD

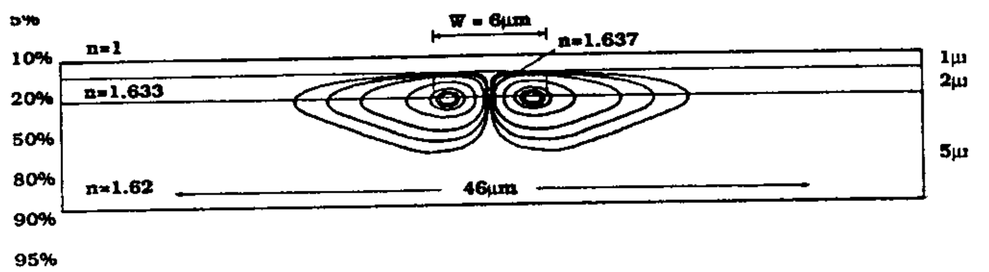


Scalar Finite Difference Method

EFFECTIVE INDEX METHOD



FINITE DIFFERENCE METHOD

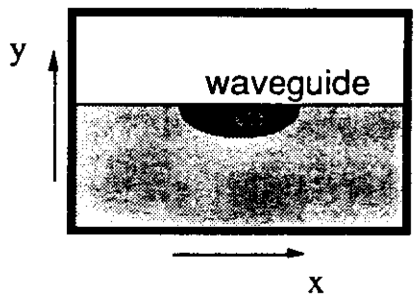


Vectorial Finite Difference Method : Theory

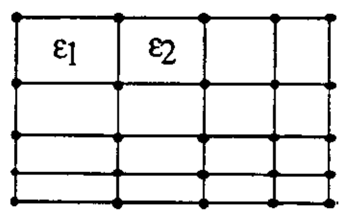
Basic equation :

(*) $$\nabla_t^2 \vec{h}_t + (k_0^2 \varepsilon_r - \beta^2)\vec{h}_t = -\frac{\vec{\nabla}_t \varepsilon_r}{\varepsilon_r} \times (\vec{\nabla}_t \times \vec{h}_t)$$

- finite cross section



- graded mesh
- each cell constant permittivity

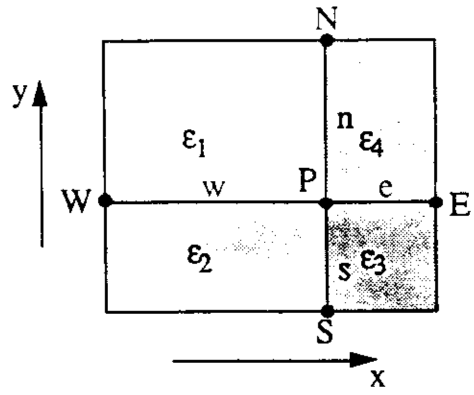


Vectorial Finite Difference Method : Theory

- 4 elementary cells :

eq(*) ⟶ $\begin{cases} \nabla_t^2 h_x^{(\upsilon)} + k_\upsilon^2 h_x^{(\upsilon)} = 0 \\ \nabla_t^2 h_y^{(\upsilon)} + k_\upsilon^2 h_y^{(\upsilon)} = 0 \end{cases}$

$$k_\upsilon^2 = k_0^2 \varepsilon_\upsilon - \beta^2$$



- finite difference representation
  + implementation of
  boundary conditions give :

$$h_{xP} = f_1\,(h_{x(W,N,E,S)},\ h_{y(W,N,E,S)})$$

$$h_{yP} = f_2\,(h_{x(W,N,E,S)},\ h_{y(W,N,E,S)})$$

(scalar case : $\Phi_P = f\,(\Phi_{W,N,E,S})$)

Vectorial Finite Difference Method : Theory - eigenvalue equation

- eigenvalue equation for NTOT node points

$$\{[A] - \lambda[U]\}\,[X] = 0$$

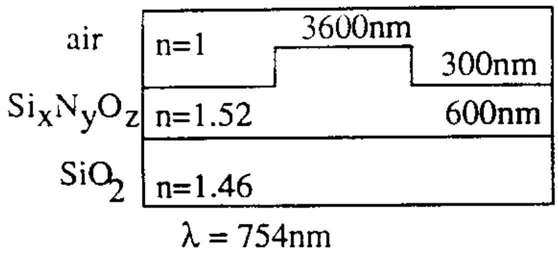
$$\lambda = \beta^2$$

$$[X] = [h_{x1},\ h_{y1},\ h_{x2},\ h_{y2},\ \ldots,\ h_{xNTOT},\ h_{yNTOT}]^T$$

- solution : a standard numerical procedure

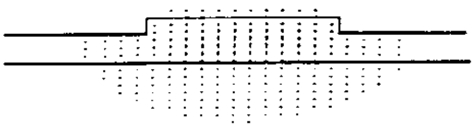
Vectorial Finite Difference Method : Example : rib waveguide 1

Waveguide geometry

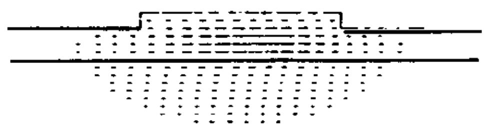


Scalar FDM :

Vectorial FDM :

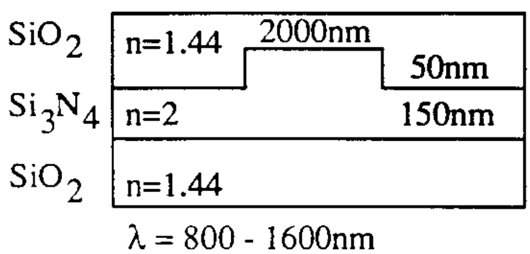


Vectorial FDM :

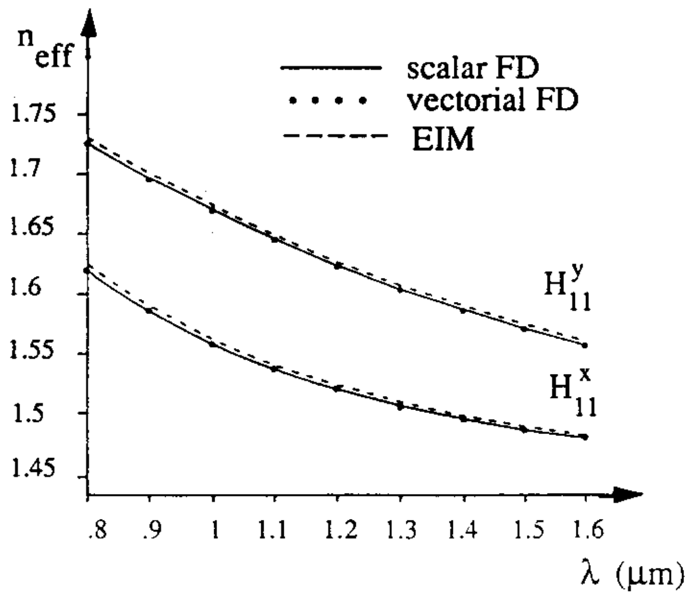


Vectorial Finite Difference Method : Example : rib waveguide 2

waveguide geometry



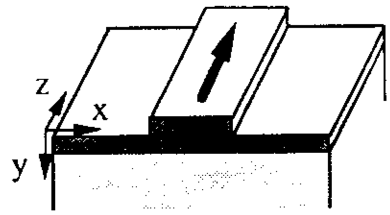
without material dispersion



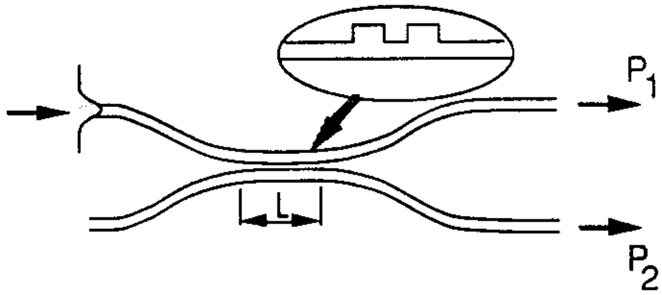
Conclusion : EIM overestimates n_{eff}

Beam Propagation Method : Introduction

- Longitudinally invariant structure



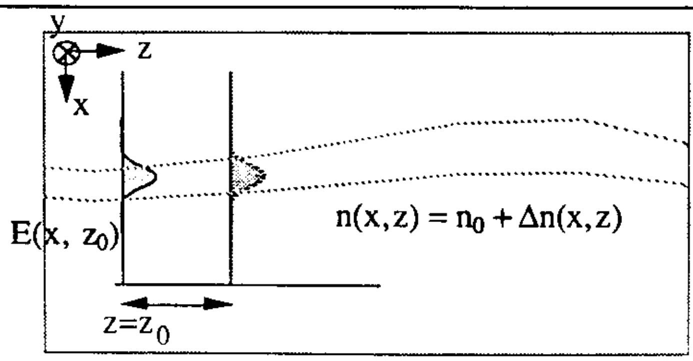
- Longitudinally variant structure



→ Coupling to radiation modes

→ *Beam Propagation Method (BPM)*

Beam Propagation Method : Formulation of Problem



- Problem :

Given $E(x, z)\big|_{z=z_0}$ → find $E(x, z)\big|_{z=z_0+\Delta z}$

→ BPM operator :

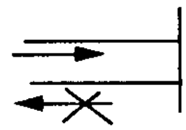
$$E(x, z_0+\Delta z) = P_{BPM} \langle E'(x, z_0) \rangle$$

$P_{BPM} = ?$

(can be used in subsequent steps along z)

Beam Propagation Method : Restrictions

- Simple solution possible if
  - propagation field is scalar
  - $\left|\frac{\Delta n}{n_0}\right| << 1$
  - no backward reflections



  - angular spectrum limited