INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

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

21 January - 15 February 1991

Physics and Technology of Semiconductor Lasers

P. Spano
Fondazione Ugo Bordoni
Roma, Italy

OUTLINE

- OUTLINE OF SEMICONDUCTOR LASER PHYSICS
- TECHNOLOGY OF SEMICONDUCTOR LASERS
- EMISSION PROCESSES IN SEMICONDUCTORS
- FABRY - PEROT LASERS
- THRESHOLD CURRENT
- CONFINEMENT OF ELECTROMAGNETIC FIELD
  - TRANSVERSE CONFINEMENT
  - LATERAL CONFINEMENT
- PHASE - LOCKED ARRAYS
- EMISSION SPECTRUM OF FABRY - PEROT LASERS
- DISTRIBUTED FEEDBACK AND DISTRIBUTED BRAGG REFLECTOR LASERS
- MODULATION PROPERTIES
- QUANTUM WELL LASERS

ADVANTAGES OF SEMICONDUCTOR LASERS

- SMALL DIMENSIONS ($\sim 400 \times 400 \times 200\ \mu m^3$)
- EASE OF EXCITATION ($V \sim 1\text{-}2$ Volt, $I_{th} \sim 50$ mA)
- EASE OF MODULATION

  HIGH SPEED OF MODULATION ($\lesssim 30$ GHz)

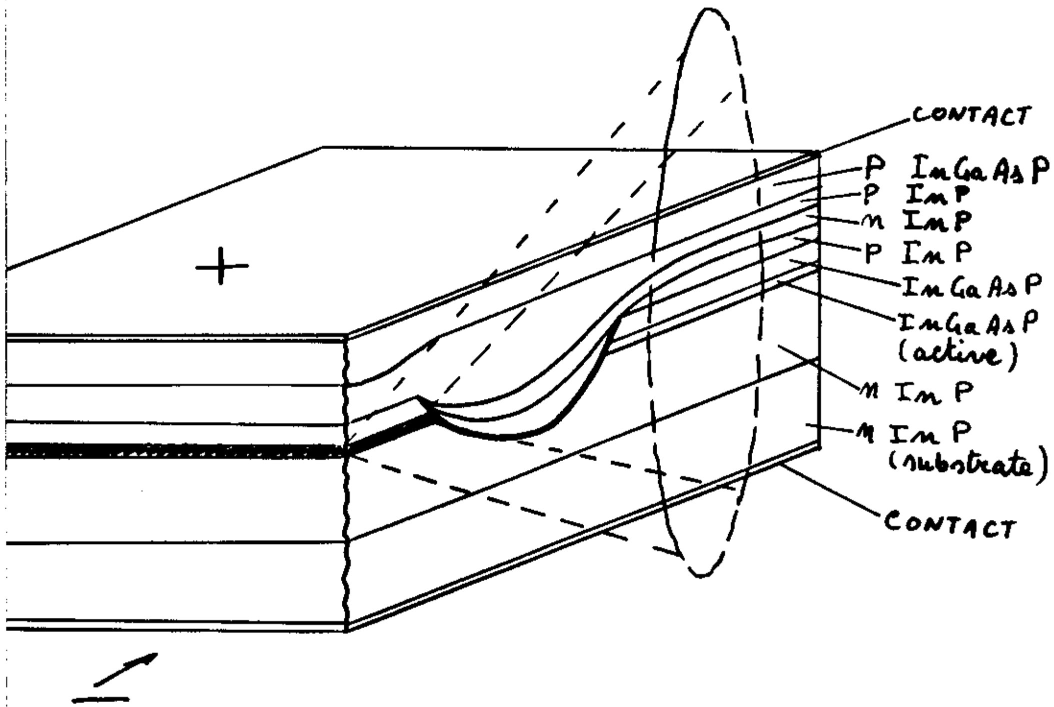
  LARGE CHOICE OF EMISSION WAVELENGTHS
  (0.6 – 3 μm
  0.3 – 100 μm)

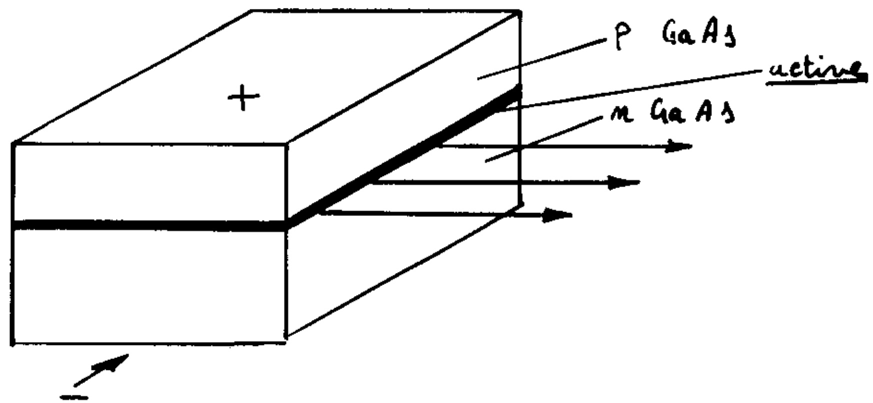
- HIGH EFFICIENCY ($\lesssim 40\%$)

PROBLEMS

- DIVERGENCE AND ASTIGMATISM OF THE BEAM
- LIMITED MAXIMUM OUTPUT POWER

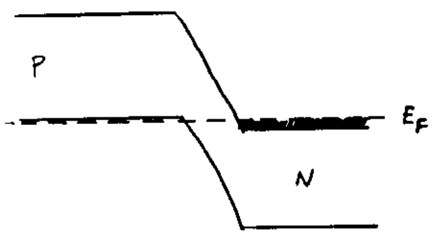
  (~ 200 mW FOR SINGLE STRIPE LASERS)



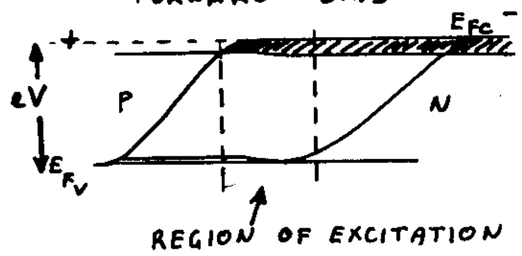


FUNDAMENTALS OF P-N JUNCTION

UNBIASED



FORWARD BIAS

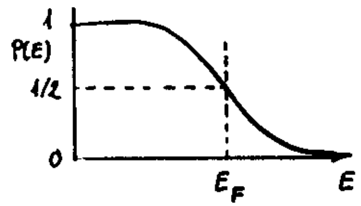


P-N HOMOJUNCTION

E_F = FERMI LEVEL

E_{Fc}, E_{F_V} = QUASI FERMI LEVELS

$$P(E) = \frac{1}{1 + \exp \frac{E - E_F}{KT}}$$



$$J = J_o \exp[(eV/KT) - 1] \quad = \text{CARRIER DENSTY}$$

$$J_o = e\left[\frac{D_h P_n}{L_h} + \frac{D_e N_p}{L_e}\right]$$

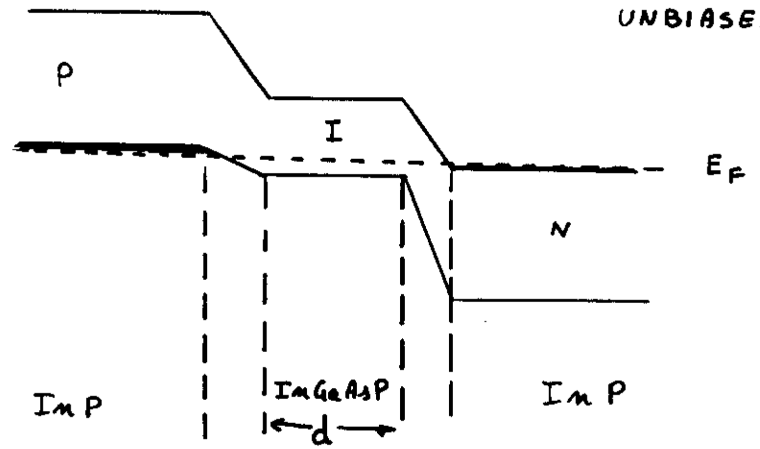
D = DIFFUSION COEFFICINT

L = DIFFUSION LENGTH ~ 1-5 μm

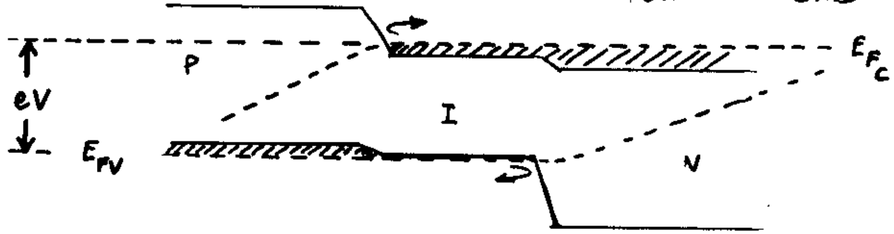
P, N = CARRIER DENSITY (HOLES, ELECTRONS)

HETEROJUNCTIONS

UNBIASED

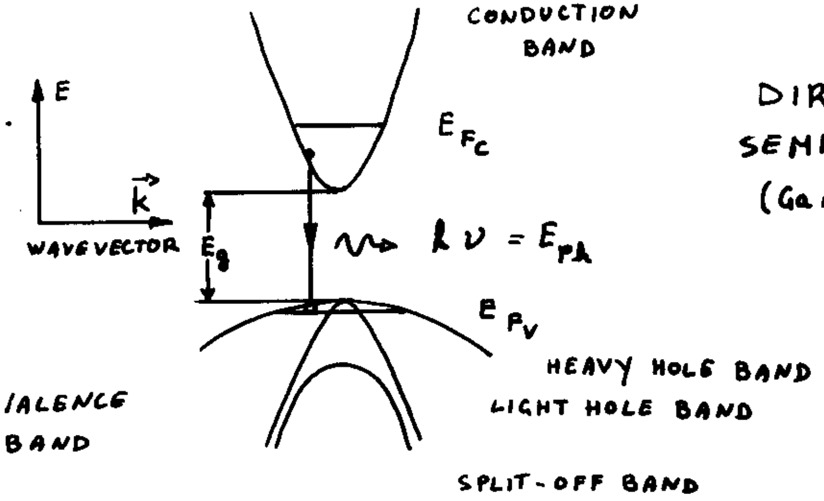


FORWARD BIAS



$0.05 < d < 0.5$ μm DH (DOUBLE HETEROJUNCTION)

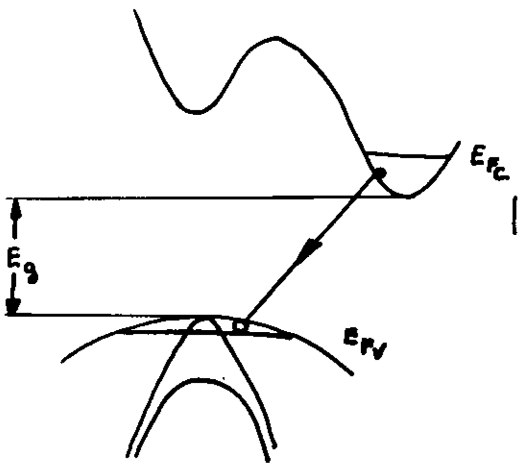
$d < 0.02$ μm QW (QUANTUM WELL)



DIRECT BAND SEMICONDUCTOR
(GaAs, InP)

$$\begin{cases} E_{el} - E_h = E_{ph} \\ \vec{K}_{el} - \vec{K}_h = \vec{K}_{ph} \end{cases} \qquad |\vec{k}_{ph}| = \frac{2\pi}{\lambda}$$

INDIRECT BAND SEMICONDUCTOR
(Ge, Si)

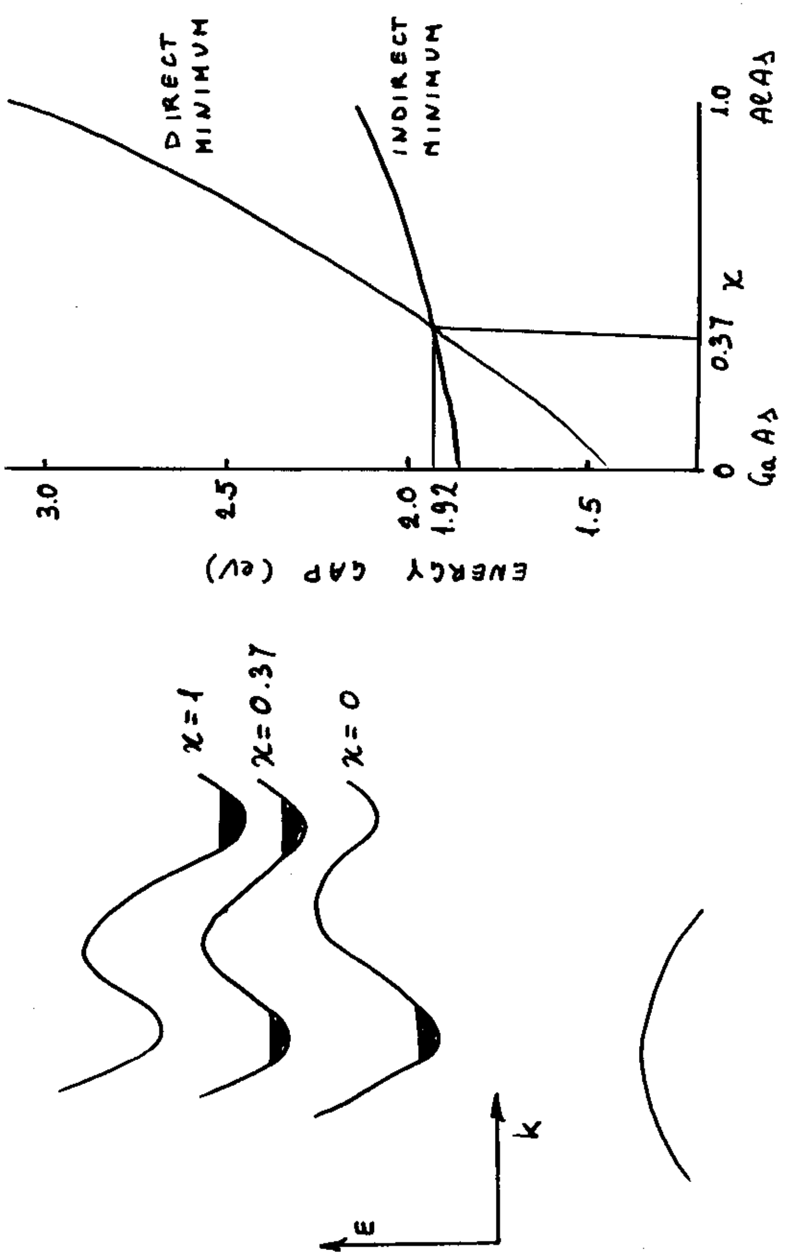


$$|\vec{K}_{el} - \vec{K}_h| \simeq \frac{2\pi}{a} \sim 1\,\text{Å}^{-1} \gg \frac{2\pi}{\lambda}$$

$$\begin{cases} E_{el} - E_h = E_{ph} + E_{phon} \\ \vec{K}_{el} - \vec{K}_h = \vec{K}_{ph} + \vec{K}_{phon} \end{cases}$$

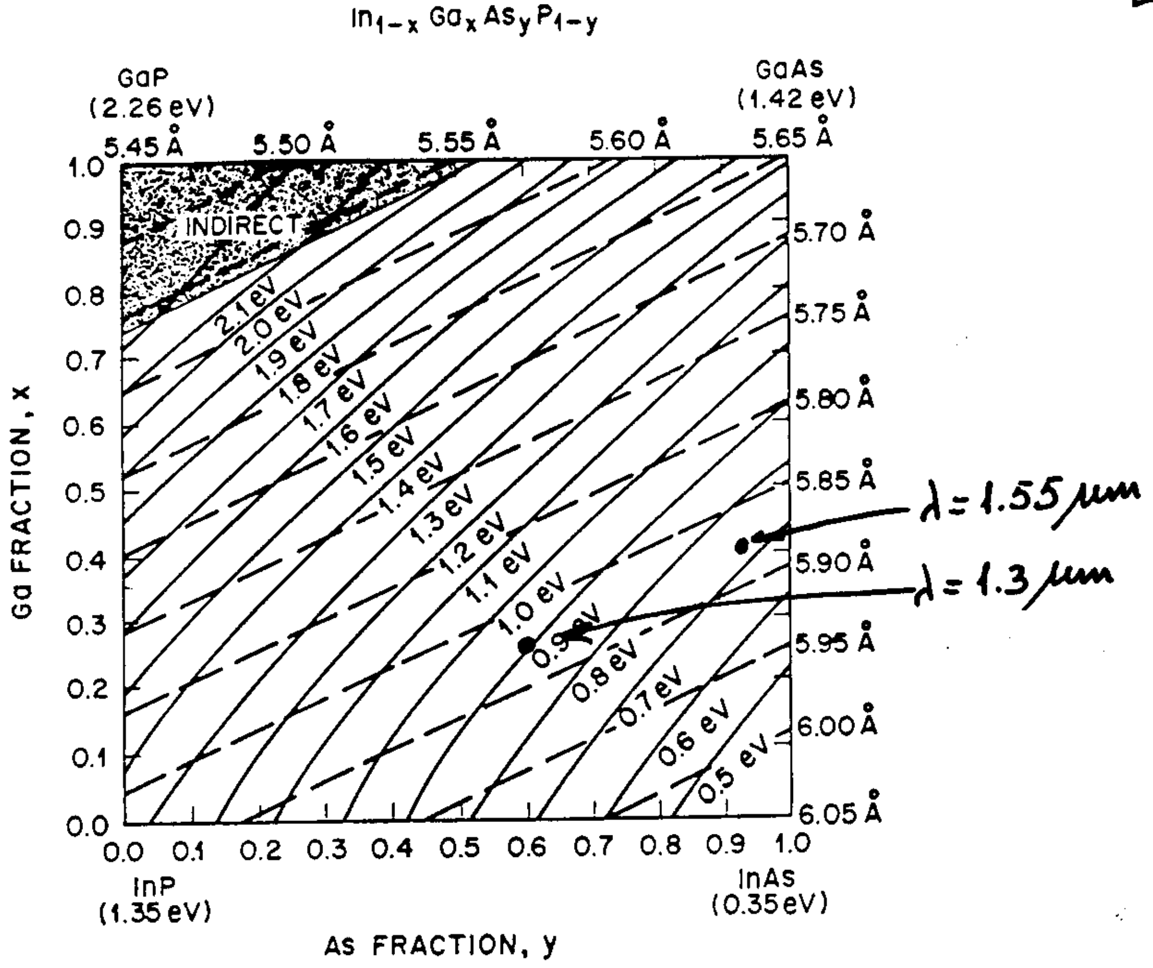
$h\nu$ CAN BE VARIED USING COMPOUND CRYSTALS

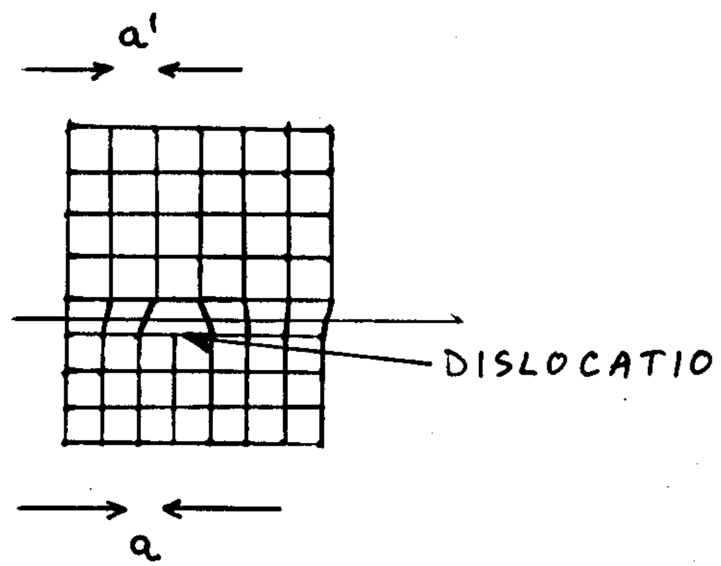
$Ga_{1-x}Al_xAs$

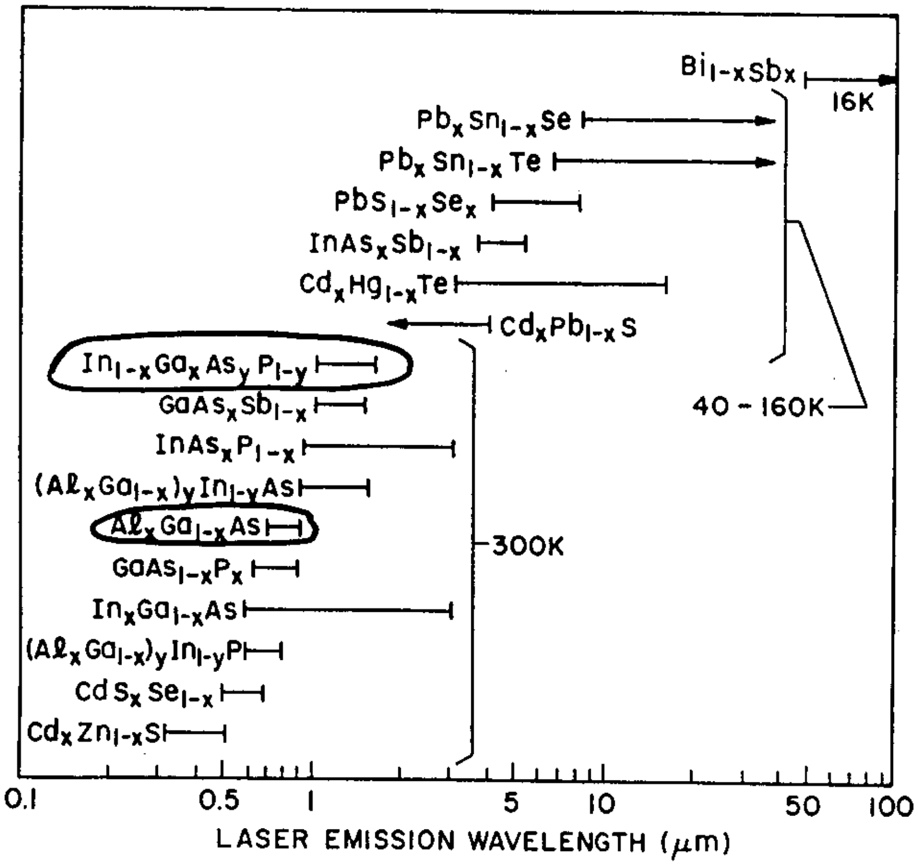


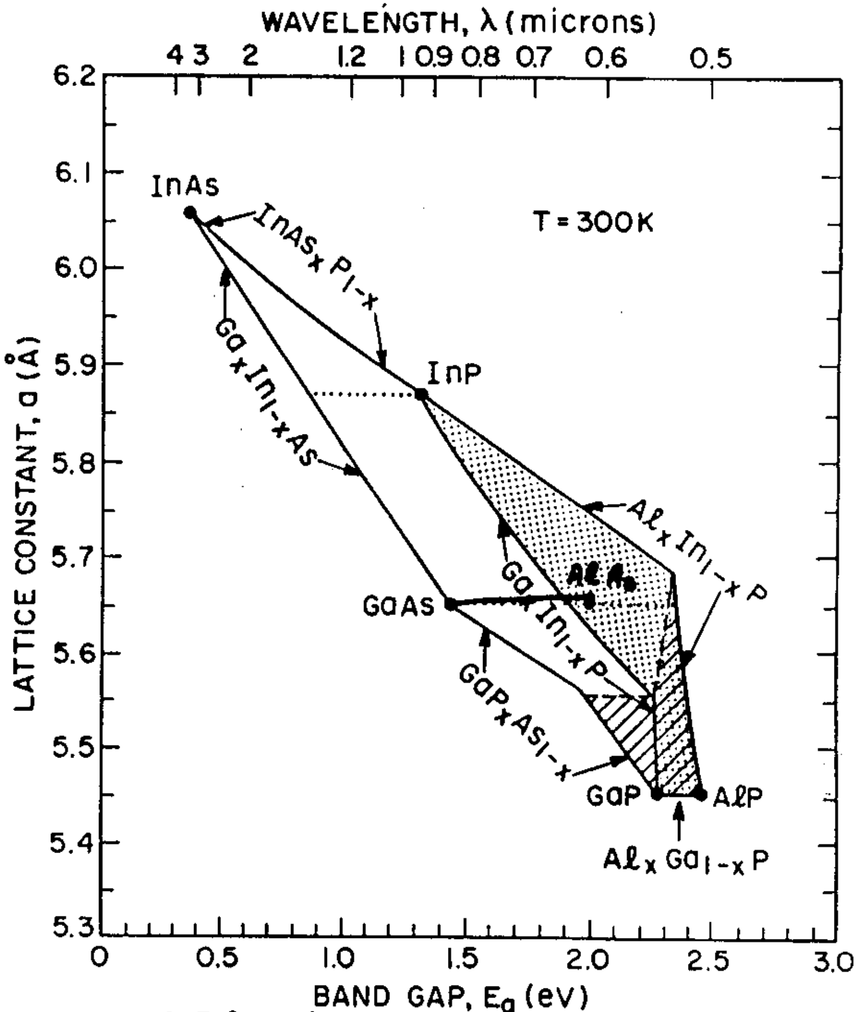
IN $In_{1-x}Ga_xAs_yP_{1-y}$ LATTICE MATCHED ON InP AT ROOM TEMPERATU

$$E_g \simeq 1.35 - 0.72\,y + 0.12\,y^2 \text{ eV}$$









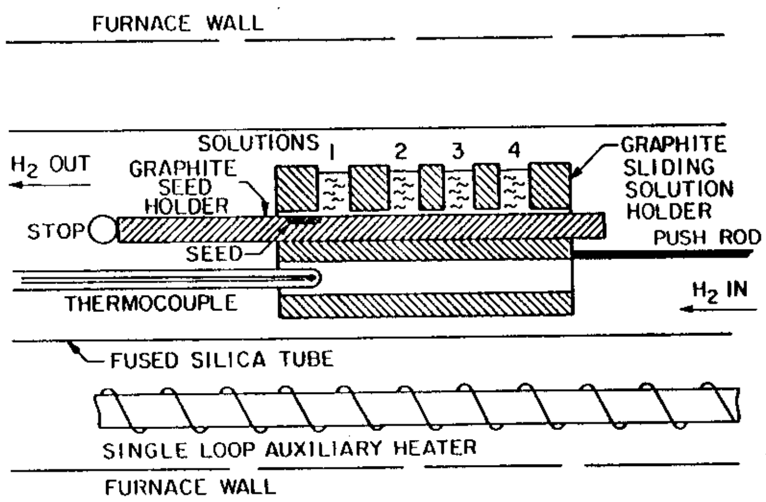
CLEAR REGION $In_{1-x}Ga_xAs_{1-y}P_y$

SHADED REGION $(Al_xGa_{1-x})_yIn_{1-y}P$

GROWTH TECHNIQUES

EPITAXY = LATTICE-MATCHED CRYSTALLINE GROWTH OF A SEMICONDUCTOR OVER ANOTHER

I) LIQUID PHASE EPITAXY (LPE)



GROWTH METHODS

a) STEP COOLING

$$d = k \Delta T t^{1/2}$$

$$\Delta T = T_0 - T$$

T_0 = SATURATION TEMPERATURE

b) EQUILIBRIUM COOLING

$$d = \frac{2}{3} k \frac{dT}{dt} t^{3/2}$$

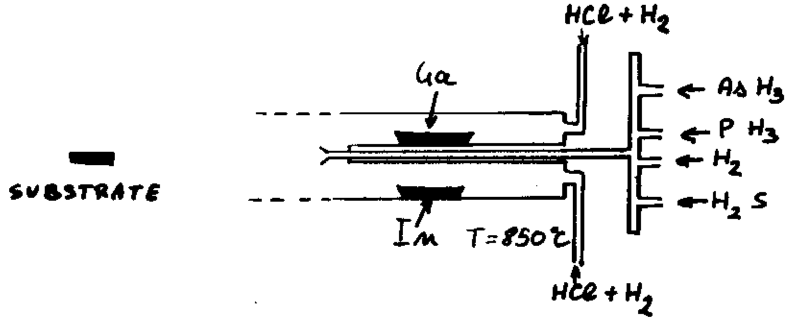
c) SUPERCOOLING

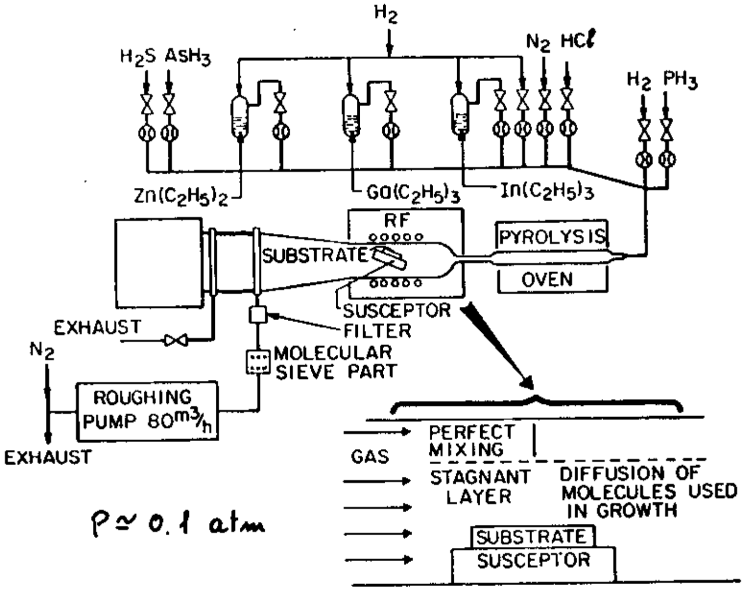
$$d = k\left(\Delta T t^{1/2} + \frac{2}{3} \frac{dT}{dt} t^{3/2}\right)$$

d) TWO PHASE TECHNIQUE

AS b) BUT WITH A SOLID MATERIAL ON TOP OF THE SOLUTION

2) VAPOR PHASE EPITAXY (VPE)





$v \simeq 1 - 15$ cm/s

$P \simeq 0.1$ atm

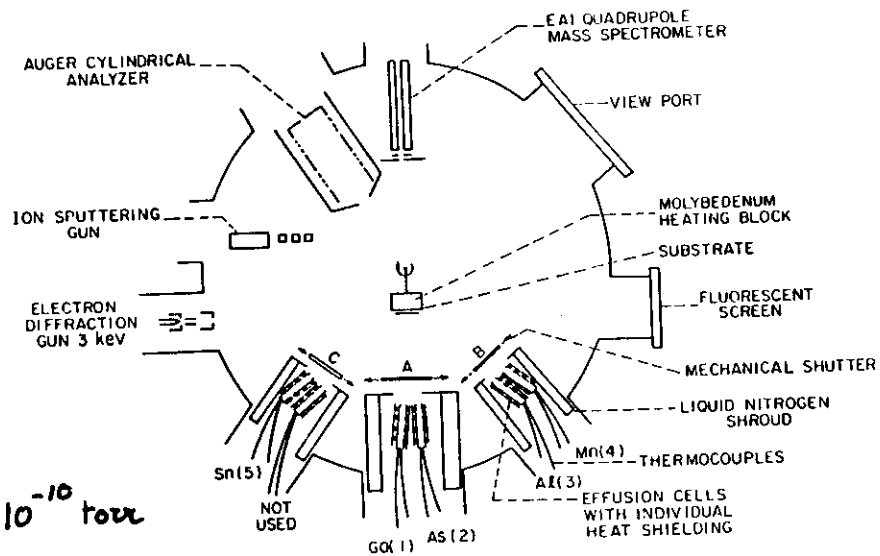
METAL-ORGANIC VAPOR-PHASE EPITAXY (MOCVD)

GROWTH RATE ~ 2-4 μm/h

3) MOLECULAR BEAM EPITAXY (MBE)

ADVANTAGES: SHARP INTERFACES
THIN LAYERS

AlGaAs



$P \sim 10^{-10}$ torr

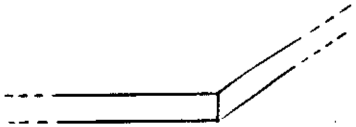
GAS CELL MBE

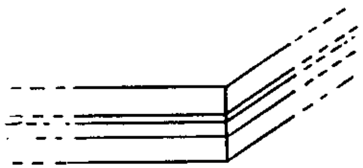
VARIANT TO SOLVE THE PROBLEMS WITH THE USE OF P IN InGaAsP. AsH_3 AND PH_3, SENT TO THE GROWTH CHAMBER, ARE DECOMPOSED AT HIGH TEMPERATURE (900 - 1200 °C) IN H_2, As_4 AND P_4. IN ANOTHER HEATED REGION AT LOW PRESSURE ($\sim 10^{-3}$ torr) As_4 AND P_4 DECOMPOSE FURTHER INTO MOLECULES OF As_2 AND P_2.

STEPS FOR LASER FABRICATION

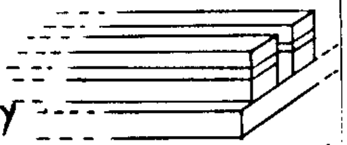
1) SELECTION AND PREPARATION OF A SUBSTRATE WAFER

- SUBSTRATE FREE OF CRYSTALLINE DEFECTS, DISLOCATIONS AND INCLUSIONS
- CHEMICAL ETCHING, POLISHING

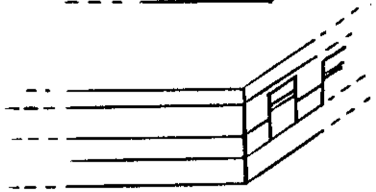




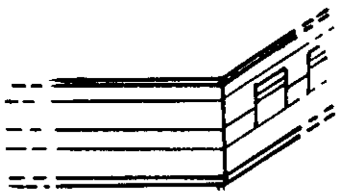
2) EPITAXIAL GROWTH OF THE VARIOUS HETEROSTRUCTURE LAYERS



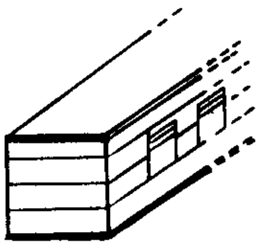
3) DELINEATION OF THE LONGITUDINAL STRIPES FOLLOWED BY PHOTOLITOGRAPHY TO OPEN UP APPROPRIATE WINDOWS



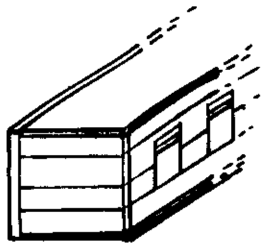
4) FURTHER EPITAXIAL GROWTH



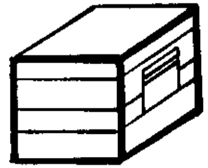
5) METALLIZATION OF THE WAFER ON BOTH SIDES



6) CLEAVING OF THE WAFER INTO BARS EQUAL IN WIDTH TO THE REQUIRED LENGTH OF THE LASER (70-600 μm)

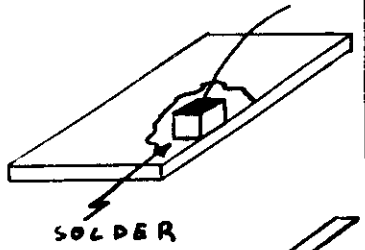


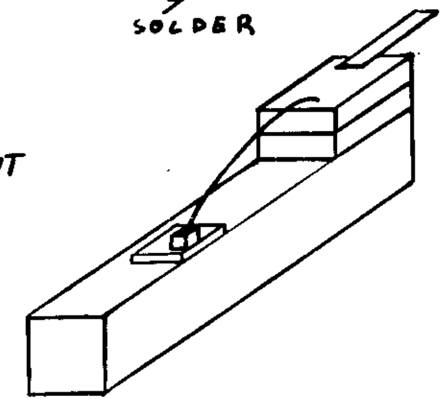
7) APPLICATION OF REFLECTION, ANTIREFLECTION OR PROTECTIVE COATINGS ON THE CLEAVED FACETS



8) SEPARATION OF BARS INTO INDIVIDUAL LASER CHIPS

9) MOUNTING OF THE LASER CHIP ONTO A HEADER BY LOW MELTING POINT, SOFT SOLDER AND ATTACHMENT OF A LEAD TO THE TOP CONTACT

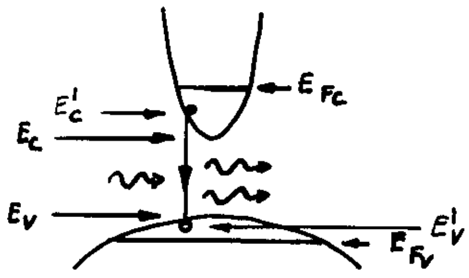




10) MOUNTING ON THE SUBMOUNT

EMISSION PROCESSES IN SEMICONDUCTOR LASERS

APPROXIMATION OF THE SINGLE ELECTRON (THE EQUILIBRIUM INSIDE THE BANDS IS MAINTAINED BY A RIDISTRIBUTION OF THE CARRIERS MUCH FASTER THAN ALL THE RECOMBINATION PROCESSES)



$$h\nu = E'_c - E'_V$$

$$p_c = \left[1 + \exp\left(\frac{E'_c - E_{Fc}}{kT}\right)\right]^{-1}$$ PROBABILITY OF FINDING AN ELECTRON AT $E = E'_c$

$$q_V = 1 - \left[1 + \exp\left(\frac{E'_V - E_{FV}}{kT}\right)\right]^{-1}$$ PROBABILITY OF FINDING A HOLE AT $E = E'_V$

$$\rho_{RED} = \frac{1}{2}\frac{\rho_c\,\rho_v}{\rho_c + \rho_v}$$ REDUCED DENSITY OF STATES

$C_{cv}(h\nu)$ PROBABILITY PER UNIT TIME OF SPONTANEOUS RECOMBINATION OF AN ELECTRON OF THE CONDUCTION BAND WITH A HOLE OF THE VALENCE BAND

$B_{cv}(h\nu)$ PROBABILITY PER UNIT TIME OF STIMULATED RECOMBINATION FOR UNIT DENSITY OF PHOTONS PER UNIT INTERVAL OF ENERGY

$B_{vc}(h\nu)$ PROBABILITY PER UNIT TIME OF ABSORPTION FOR UNIT DENSITY OF PHOTONS

$$r'_{sp}(h\nu) = C_{cv}\,\rho_{red}\,p_c\,q_V$$ SPONTANEOUS EMISSION RATE BETWEEN THE STATES AT ENERGY E'_c AND E'_V

$$r^{d}_{st}(h\nu) = B_{cv}\,\rho_{red}\,p_c\,q_V\,\tilde{N}$$ STIMULATED EMISSION RATE

$$r^{u}_{st}(h\nu) = B_{vc}\,\rho_{red}\,(1-p_c)(1-q_V)\,\tilde{N}$$ ABSORPTION RATE

AT EQUILIBRIUM

$$C_{cv}\,p_c\,q_V + B_{cv}\,\tilde{N}_0\,p_c\,q_V = B_{vc}\,\tilde{N}_0\,(1-p_c)(1-q_V)$$

$$\tilde{N}_0 = \frac{8\pi\,\bar{n}^3(h\nu)^2}{h^3c^3}\langle n^0_\nu\rangle = \frac{8\pi\,\bar{n}^3(h\nu)^2}{h^3c^3[\exp(h\nu/kT)-1]}$$

$$\Downarrow$$

$$B_{cv} = B_{vc}$$

$$C_{cv} = \frac{8\pi\,\bar{n}^3(h\nu)^3}{h^3c^3}B_{cv} = Z(h\nu)\,B_{cv}$$

$$r'_{st}(h\nu) = \frac{r_{st}^{d}(h\nu) - r_{st}^{u}(h\nu)}{\langle n_\nu \rangle} =$$

$$= B_{cv}\,\rho_{red}\, Z \quad p_c\, q_v \left[1 - \frac{(1-p_c)(1-q_v)}{p_c\, q_v}\right] =$$

$$= C_{cv}\,\rho_{red}\, p_c\, q_v \left[1 - \exp\left(\frac{h\nu - \Delta E_F}{kT}\right)\right] =$$

$$= r'_{sp}(h\nu)\left[1 - \exp\left(\frac{h\nu - \Delta E_F}{kT}\right)\right]$$

$$r_{sp}(h\nu) = \int_{-\infty}^{\infty} r'_{sp}(E'_c, h\nu)\, \rho_c(E'_c)\, dE'_c$$

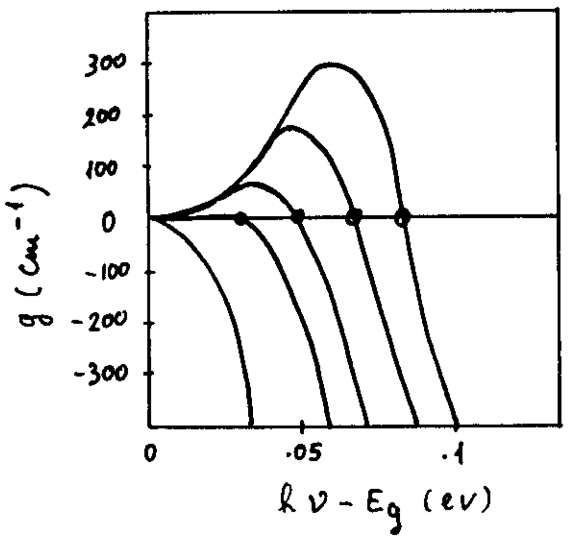
$$r_{st}(h\nu) = r_{sp}(h\nu)\left[1 - \exp\left(\frac{h\nu - \Delta E_F}{kT}\right)\right]$$

$$g(h\nu) = \frac{\text{OPTICAL POWER EMITTED PER UNIT VOLUME}}{\text{OPTICAL POWER INCIDENT PER UNIT AREA}}$$

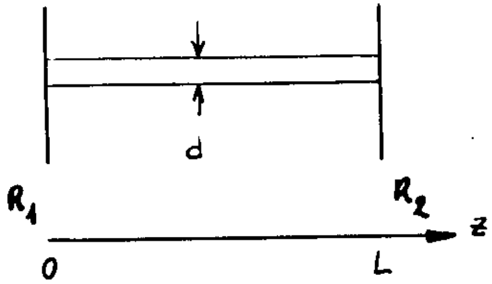
$$g(h\nu) = \frac{h\nu \langle n_\nu \rangle\, r_{st}(h\nu)}{h\nu\,(c/\bar{n})\,\langle n_\nu \rangle\, Z} =$$

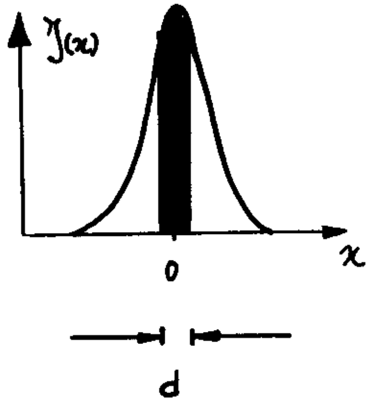
$$\frac{c^2 h^3}{8\pi\, \bar{n}^2 (h\nu)^2}\, r_{sp}(h\nu)\left[1 - \exp\left(\frac{h\nu - \Delta E_F}{kT}\right)\right]$$

$g > 0$ $$\boxed{E_g < h\nu < \Delta E_F}$$



FABRY-PEROT SEMICONDUCTOR LASERS





FOR STIMULATED EMISSION >> SPONTANEOUS EMISSION

$$I_{h\nu}(z) = I_{h\nu}(0)\,\exp\left\{\left[g(h\nu)\Gamma - \bar{\alpha}(h\nu)\right]z\right\}$$

$\bar{\alpha}$ = SCATTERING LOSSES

$$\Gamma = \frac{\int_{-d/2}^{d/2} I(x)\,dx}{\int_{-\infty}^{\infty} I(x)\,dx} = \text{CONFINEMENT FACTOR}$$

FOR FIELDS PHASE-MATCHED OVER A ROUND-TRIP

$$\exp(i2\beta L) = 1 \Rightarrow 2\beta L = 2\pi q \Rightarrow q\lambda_q = 2\bar{n}L$$

$$I_{h\nu}(2L) = R_1R_2\,I_{h\nu}(0)\,\exp\left\{\left[g(h\nu)\Gamma - \bar{\alpha}(h\nu)\right]2L\right\}$$

THRESHOLD CONDITION

$$I_{h\nu}(2L) = I_{h\nu}(0)$$

$$\Downarrow$$

$$\Gamma g(h\nu) = g_{th} = \bar{\alpha}(h\nu) + \frac{1}{2L}\ln\frac{1}{R_1R_2}$$

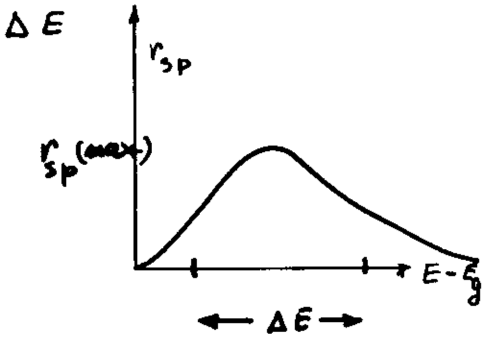
THRESHOLD CURRENT

AT THRESHOLD

$$J_{th} = \frac{I_{th}}{S} = e\frac{ds}{\eta s}\int_0^\infty r_{sp}(h\nu)\,d h\nu = \frac{ed}{\eta}R =$$

$$= \frac{ed}{\eta}\,r_{sp}(h\nu_{max})\,\Delta E$$

η = QUANTUM EFFICIENCY



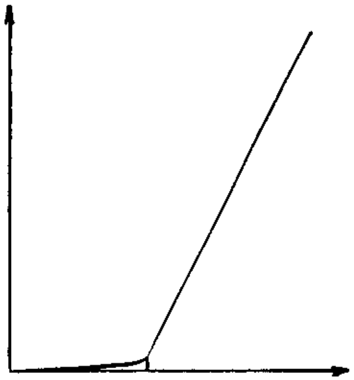
$$J_{th} = \frac{ed}{\eta}\,\frac{r_{st}(h\nu_{max})}{\gamma}\,\Delta E =$$

$$= \frac{ed}{\eta}\,\frac{\Delta E}{\gamma}\,\frac{8\pi\bar{n}^2(h\nu)^2}{c^2h^3}\,g_{max}$$

$$g_{max} = \frac{g_{th}}{\Gamma}$$

$$\begin{cases} J_{th} = J_{nom}\dfrac{d}{\eta\Gamma} \\ J_{nom} = e\dfrac{8\pi\bar{n}^2(h\nu)^2}{\gamma}\,\Delta E\left(\dfrac{1}{2L}\ln\dfrac{1}{R_1R_2} + \bar{\alpha}\right) \end{cases}$$

CHARACTERISTICS P-I



EXTERNAL EFFICIENCY

$$\Delta\eta = \frac{\Delta P / h\nu}{\Delta I / e} = \frac{\text{INCREMENT OF EMITTED PHOTON FLUX A.T}}{\text{INCREMENT OF ELECTRON FLUX}}$$

$$\Delta\eta \cong \frac{\Delta P / E_g}{\Delta I / e} \simeq \frac{\Delta P}{\Delta I\ V} \approx \frac{P}{(I - I_{th})V}$$

$$\Delta\eta = \frac{\Gamma(g_{th} - \bar{\alpha})}{\Gamma\ g_{th} / \eta} = \boxed{\eta \frac{\frac{1}{2L} \ln \frac{1}{R_1 R_2}}{\frac{1}{2L} \ln \frac{1}{R_1 R_2} + \bar{\alpha}}}$$

$$J_{th} = J_{nom} \frac{e\,d}{\eta\,\Gamma}$$

$$J_{nom} \propto \frac{1}{2L} \ln \frac{1}{R_1 R_2} + \bar{\alpha} = \frac{1}{2L} \ln \frac{1}{R_1 R_2} + \Gamma \bar{\alpha}_{fc} + (1-\Gamma)\bar{\alpha}_i$$

HOMOJUNCTION LASERS

$d \simeq L_e \sim 2\ \mu m$

$\Gamma < 0.1$ $\qquad$ $J_{th} \sim 50 - 80\ kA/cm^2$

$\eta = 0.9$

$\bar{\alpha}_i \simeq 50\ cm^{-1}$

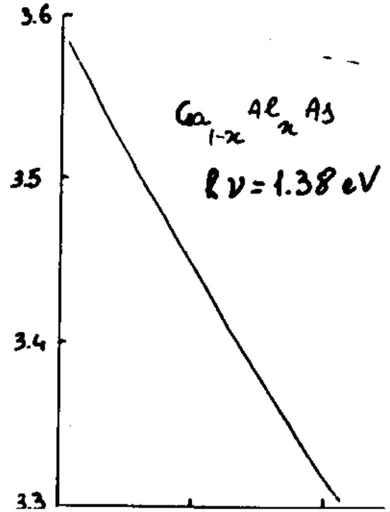
HETEROJUNCTION LASERS

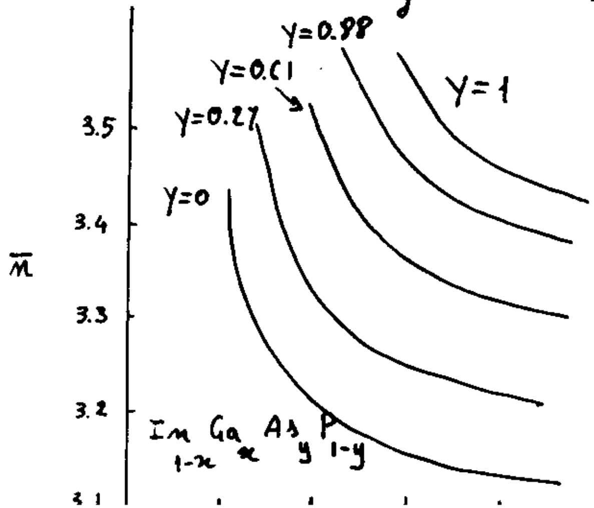
$\bar{\alpha}_i \simeq 5\ cm^{-1}$

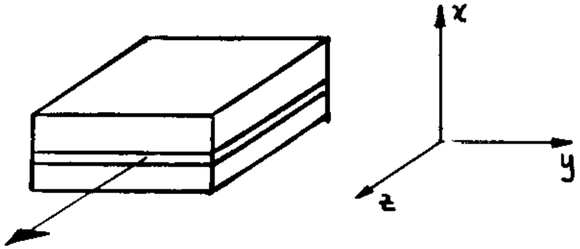
$d \lesssim 0.1\ \mu m$

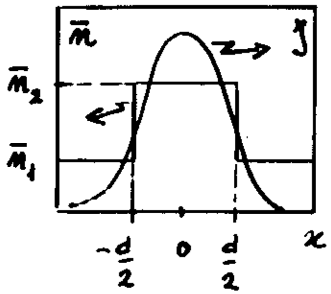
$\boxed{\Gamma\ ?}$

REFRACTIVE INDEX INCREASES WHEN E_g DECREASES









PASSIVE WAVEGUIDES

$$\nabla^2 \underline{\mathcal{E}} = \mu_0 \varepsilon \frac{\partial^2 \underline{\mathcal{E}}}{\partial t^2}$$

INFINITE STRUCTURE IN DIRECTION Y $\Rightarrow \dfrac{\partial}{\partial y} = 0$

$$\frac{\partial^2 \mathcal{E}_y}{\partial x^2} + \frac{\partial^2 \mathcal{E}_y}{\partial z^2} = \mu_0 \varepsilon \frac{\partial^2 \mathcal{E}_y}{\partial t^2}$$

$$\begin{cases} \mathcal{E}_y = \exp[i(\omega t - \beta z)]\,[A \exp(ipx) + B \exp(-ipx)] \\ p^2 = \omega^2 \mu_0 \varepsilon - \beta^2 \end{cases}$$

$$\underline{\nabla} \times \underline{\mathcal{E}} = -\mu_0 \frac{\partial \underline{H}}{\partial t}$$

$$\Downarrow$$

$$\begin{cases} H_z = \dfrac{i}{\omega \mu_0} \dfrac{\partial \mathcal{E}_y}{\partial x} \\ H_x = -\dfrac{i}{\omega \mu_0} \dfrac{\partial \mathcal{E}_y}{\partial z} \end{cases}$$

MODES TE $\mathcal{E}_y, H_z, H_x$

MODES TM $H_y, \mathcal{E}_z, \mathcal{E}_x$

THE FIELD IS CONFINED IN THE ACTIVE LAYER IF

$$\mathcal{E} \to 0 \quad \text{FOR} \quad x \to \pm\infty$$

$$\Downarrow$$

$$p^2 < 0 \quad \text{FOR} \quad x < -\frac{d}{2}\,,\; x > \frac{d}{2}$$

$$\omega^2 \mu_0 \varepsilon_1 - \beta^2 < 0$$

$$p^2 > 0 \quad \text{FOR} \quad -\frac{d}{2} < x < \frac{d}{2}$$

$$\omega^2 \mu_0 \varepsilon_2 - \beta^2 > 0$$

$$\Downarrow$$

$$\varepsilon_2 > \varepsilon_1$$

$$\mathcal{E}_y = \exp[i(\omega t - \beta z)] \begin{cases} A_1 \exp\left[q_1\left(\frac{d}{2} + x\right)\right] & x < -\frac{d}{2} \\ A_2 \cos p_2 x + A_0 \sin p_2 x & -\frac{d}{2} < x < \frac{d}{2} \\ A_2 \exp\left[-q_1\left(x - \frac{d}{2}\right)\right] & x > \frac{d}{2} \end{cases}$$

$$p_2 = (\omega^2 \mu_0 \varepsilon_2 - \beta^2)^{1/2} \qquad q_1 = (\beta^2 - \omega^2 \mu_0 \varepsilon_1)^{1/2}$$

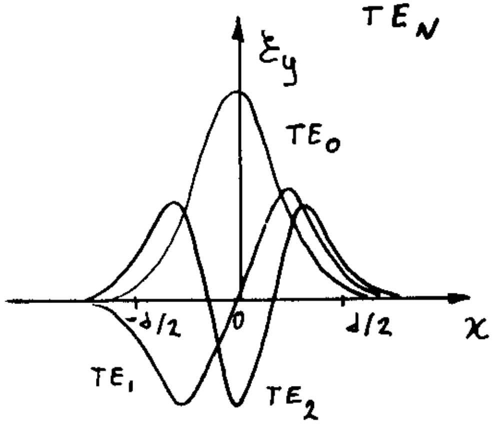
BOUNDARY CONDITIONS GIVEN BY THE CONTINUITY AT THE INTERFACES FOR THE PARALLEL COMPONENT OF THE FIELD $\mathcal{E}_y$, H_z

$$\operatorname{tg} p_2 d = 2 \frac{q_1}{p_2} \Big/ \left(1 - \frac{q_1^2}{p_2^2}\right)$$

RESULTS

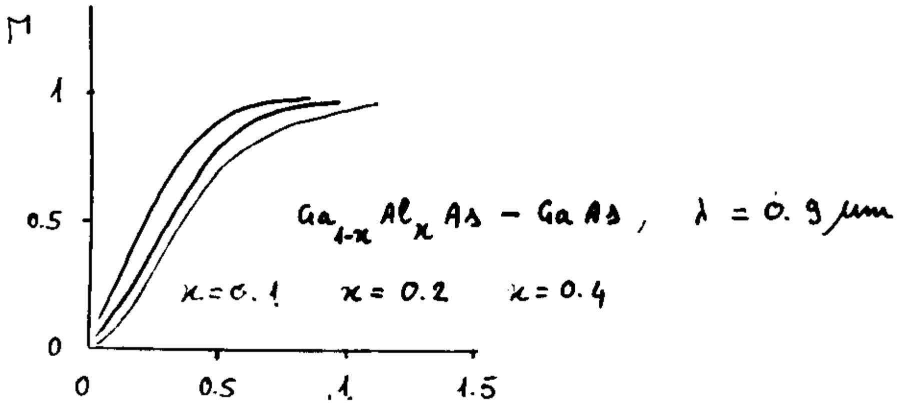
N POSSIBLE SOLUTION FOR $(N-1)\pi \leq D < N\pi$

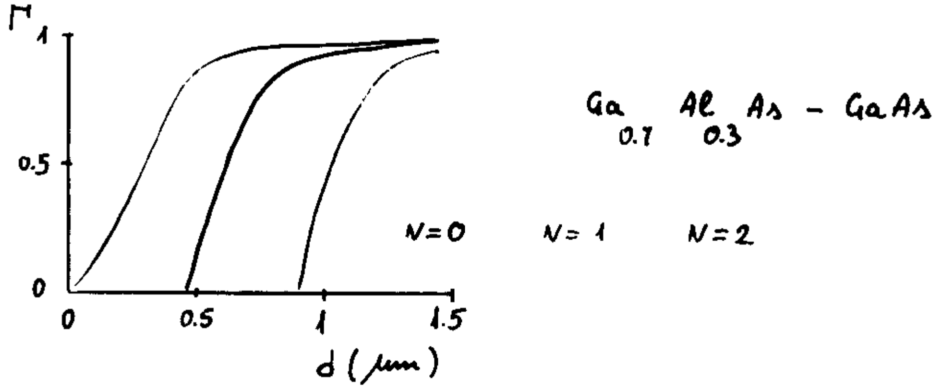
$$D = \left[\omega^2 \mu_0 \varepsilon_0 (n_2^2 - n_1^2)\right]^{1/2} d$$



$$\Gamma = \frac{\int_{-d/2}^{d/2} \mathrm{Re}\{\underline{\mathcal{E}} \times \underline{H}^*\} \cdot \underline{n}\, dx}{\int_{-\infty}^{\infty} \mathrm{Re}\{\underline{\mathcal{E}} \times \underline{H}^*\} \cdot \underline{n}\, dx}$$

$$\Gamma = \left[1 + \frac{\cos p_2 \frac{d}{2}}{q_1\left[\frac{d}{2} + \frac{1}{p_2}\sin\left(p_2 \frac{d}{2}\right)\cos\left(p_2\frac{d}{2}\right)\right]}\right]^{-1} \quad \text{FOR } N \text{ EVEN}$$



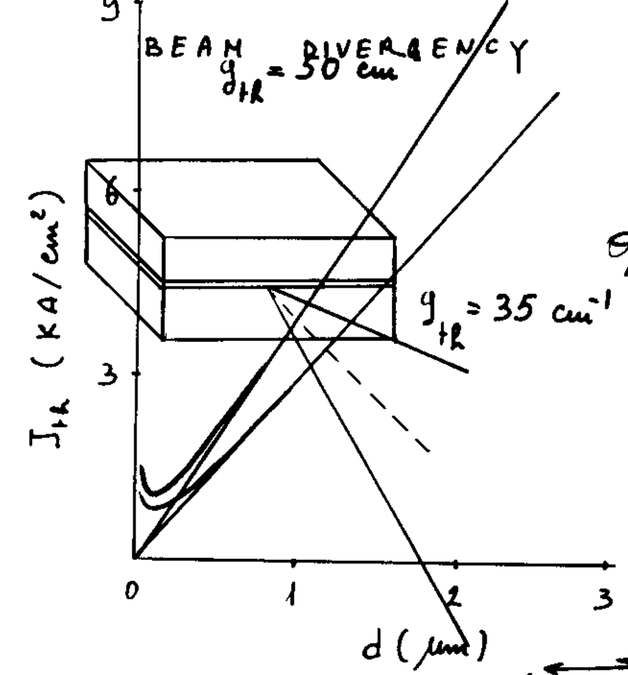


$$J_{th} \propto \frac{d}{\Gamma \eta}\left(\frac{1}{2L} \ln \frac{1}{R_1 R_2} + \bar{\alpha}\right)$$

- DECREASING d, J_{th} DECREASES AS LONG AS $\Gamma(d)$ DECREASES MORE SLOWLY THAN d.
- THE REFLECTIVITY FOR TM MODES IS LOWER THAN FOR TE MODES. THE OUTPUT IS POLARIZED WITH THE ELECTRIC VECTOR PARALLEL TO THE JUNCTION PLANE.

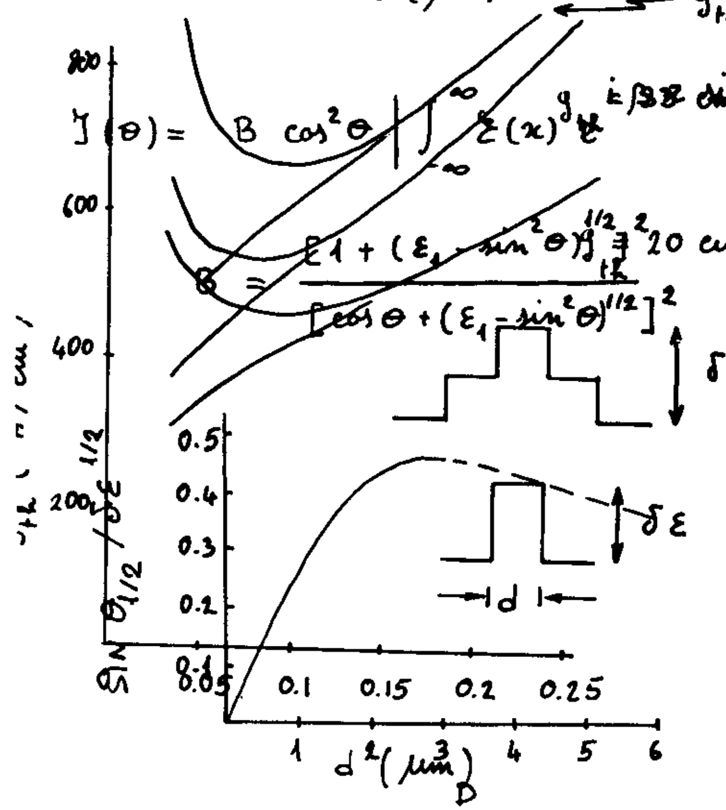
FURTHER CONSEQUENCES OF HIGH VALUE OF Γ

- HIGH VALUE OF THE BEAM DIVERGENCY



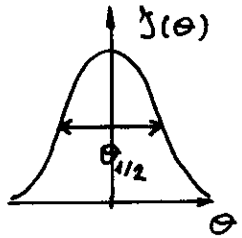
Ga Al As

$$\theta_{max} \approx \frac{\lambda}{d}\,\varepsilon_2 - \varepsilon_d = 1.6$$



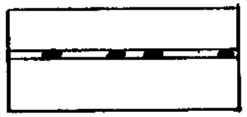
$$J(\theta) = B\cos^2\theta \left| \int_{-\infty}^{\infty} \mathcal{E}(x)\, e^{i\beta x \sin\theta}\, dx \right|^2$$

$$B = \frac{\left[1 + (\varepsilon_1 - \sin^2\theta)^{1/2}\right]^2}{\left[\cos\theta + (\varepsilon_1 - \sin^2\theta)^{1/2}\right]^2}$$



PROBLEMS LINKED TO LATERAL DIMENSIONS OF THE JUNCTION

- STRONGLY ASYMMETRIC FIELD (NEAR FIELD ~ 1 × 100 μm²)
- HIGH CURRENT THRESHOLD ($J_{th} \times 2\times10^{-2} \times 10^{-2}$ ~ 0.5 A)
- FILAMENTATION



PHYSICAL ORIGIN OF FILAMENTATION

IN ACTIVE (OR ABSORBING) MEDIA

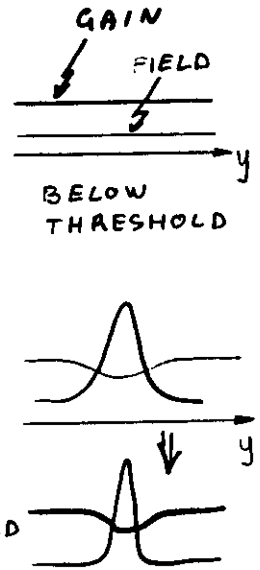
$$\beta \longrightarrow \beta + i\,\frac{g}{2} \quad \Longrightarrow \quad \varepsilon = \varepsilon_r + i\,\varepsilon_i$$

$$\begin{cases} \varepsilon_i = \varepsilon_r^{1/2}\, g / 2k_0 \\ \varepsilon_r = \varepsilon_p - \dfrac{g^2}{4k_0^2} \end{cases} \qquad k_0 = \omega^2 \mu_0 \varepsilon_0$$

DUE TO LOCAL VARIATION OF DOPING, WIDTH AND SO ON, THE LASING ACTION STARTS AT A PARTICULAR Y POSITION ALONG THE JUNCTION.

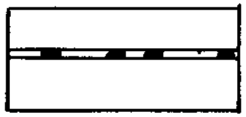
THE LASER ACTION LOCALLY DEPLETES THE CARRIERS DECREASING THE GAIN.

BECAUSE OF THE ABOVE RELATIONSHIP ONE CAN OBSERVE AN INCREASE OF THE ε_r VALUE AND HENCE THE SELF-FOCUSING OF THE FIELD WITH FORMATION OF ONE FILAMENT.



PROBLEMS LINKED TO LATERAL DIMENSIONS OF THE JUNCTION

- STRONGLY ASYMMETRIC FIELD
  (NEAR FIELD $\sim 1 \times 100\ \mu m^2$)
- HIGH CURRENT THRESHOLD $(J_{th} \times 2\times10^{-2} \times 10^{-2} \sim 0.5\,A)$
- FILAMENTATION



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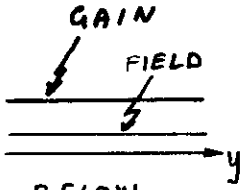
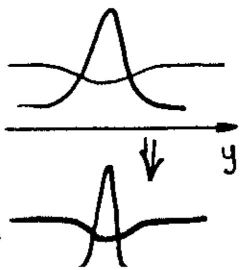


DUE TO LOCAL VARIATION OF DOPING, WIDTH AND SO ON, THE LASING ACTION STARTS AT A PARTICULAR Y POSITION ALONG THE JUNCTION.

THE LASER ACTION LOCALLY DEPLETES THE CARRIERS DECREASING THE GAIN. BECAUSE OF THE ABOVE RELATIONSHIP ONE CAN OBSERVE AN INCREASE OF THE ε_r VALUE AND HENCE THE SELF-FOCUSING OF THE FIELD WITH FORMATION OF ONE FILAMENT.

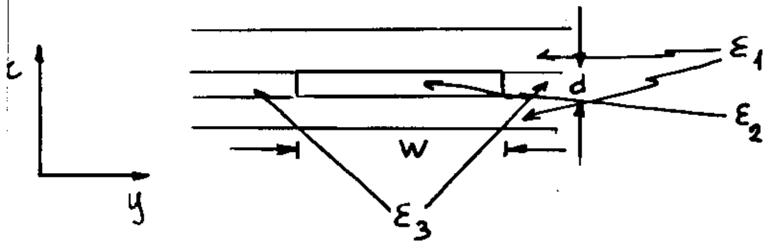


SOLUTIONS

STRIPE SEMICONDUCTOR LASERS

- GAIN GUIDED LASERS
- INDEX GUIDED LASERS
  - WEAKLY INDEX GUIDED
  - STRONGLY INDEX GUIDED

EFFECTIVE INDEX APPROXIMATION



$\varepsilon_2 - \varepsilon_3 \ll \varepsilon_2 - \varepsilon_1$ AND/OR $W \gg d$

TYPICAL VALUES

x	$d \sim 0.1\ \mu m$	$\varepsilon_2 - \varepsilon_1 \sim 1.5$
y	$w \sim 2 - 15\ \mu m$	$\varepsilon_2 - \varepsilon_3 \sim 1.5 - 0.1$

FIRST STEP

SOLVE THE PROPAGATION ACCOUNTING FOR AN INFINITE LAYER IN Y DIRECTION $\Rightarrow \mathcal{E}_y(x)$

SECOND STEP

SOLVE THE PROPAGATION ACCOUNTING FOR AN INFINITE LAYER IN X DIRECTION AND CHARACTERIZED BY AN EFFECTIVE VALUE OF $\varepsilon_{eff}(y) \Rightarrow \mathcal{E}_y(y)$

■ IN THE CASE OF INDEX GUIDED LASERS

$$\varepsilon_{eff}(y) = \varepsilon_a \qquad y > \frac{W}{2}, \quad y < -\frac{W}{2}$$

$$\varepsilon_{eff}(y) = \varepsilon_b \qquad -\frac{W}{2} < y < \frac{W}{2}$$

IN THE CASE OF GAIN GUIDED LASERS

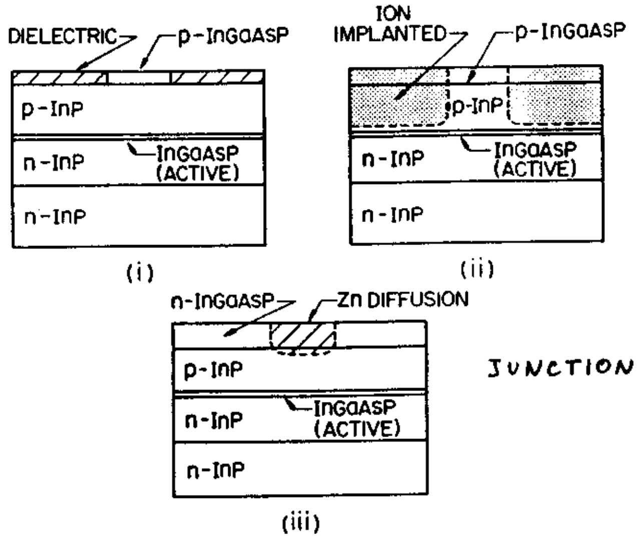
ONE SHOULD SOLVE THE EQUATION FOR THE FIELD SELF CONSISTENTELY WITH THE EQUATION

$$\frac{d^2N}{dy^2} + \frac{J(y)}{ed} - \frac{N}{\tau} - A\, g(y)\, \mathcal{I}(y) = 0$$

$$\Downarrow$$

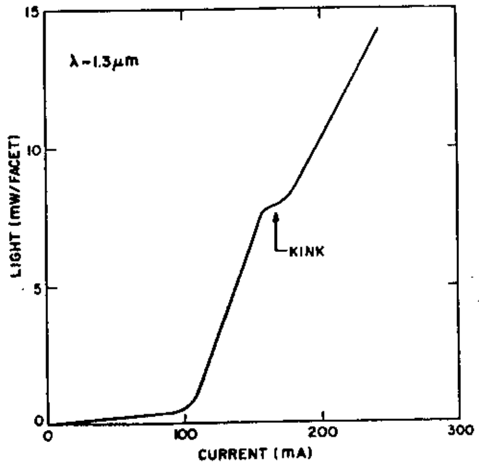
$$N(y) \Rightarrow \begin{matrix} Re(\varepsilon_{eff}) \\ Im(\varepsilon_{eff}) \end{matrix}$$

OXIDE DEFINED



PROTON IMPLANTED

JUNCTION STRIPE



ADVANTAGES

TECHNOLOGICAL EASE

DISADVANTAGES

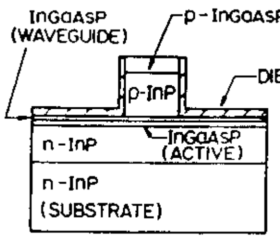
HIGH THRESHOLD CURRENT

SPATIAL INSTABILITY OF THE FIELD

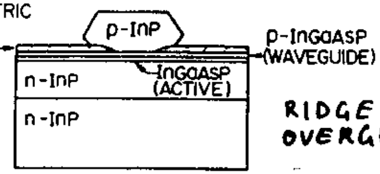
SELF PULSATIONS

WEAKLY INDEX GUIDED LASERS

DGE AVEGUIDE



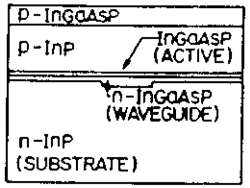
(i)



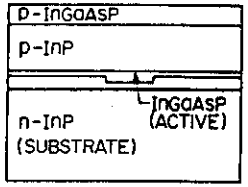
(ii)

RIDGE OVERGROWN

ANNEL BSTRATE ANAR AVEGUIDE



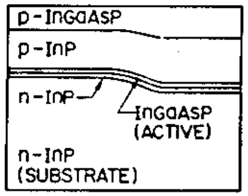
(iii)



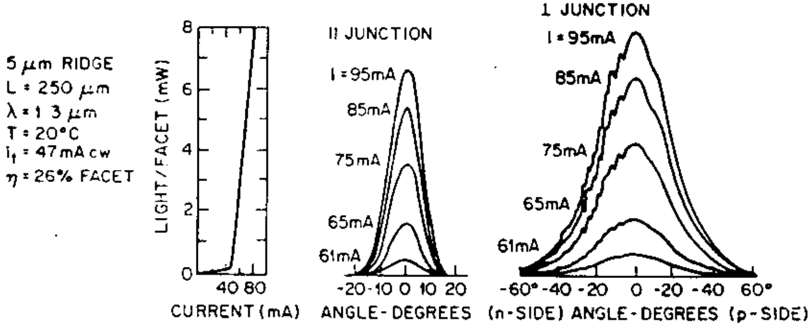
(iv)

SIMPLE RIB WAVEGUIDE

TERRACED SUBSTRATE



(v)

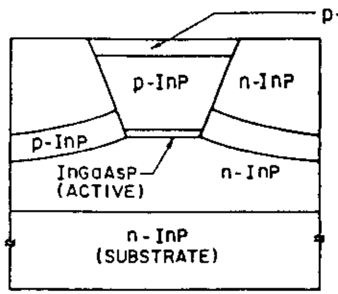


ADVANTAGES: TECHNOLOGICAL EASE

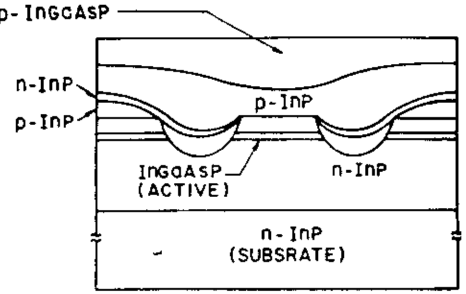
DISADVANTAGES: SPATIAL INSTABILITY AT HIGH POWER

STRONGLY INDEX GUIDED LASERS (BURIED)

ETCHED MESA BURIED HETEROS.



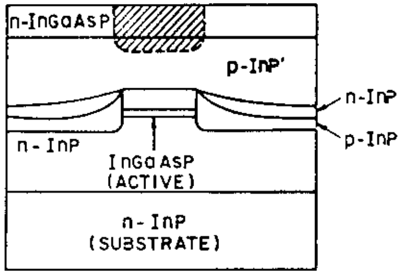
(i)



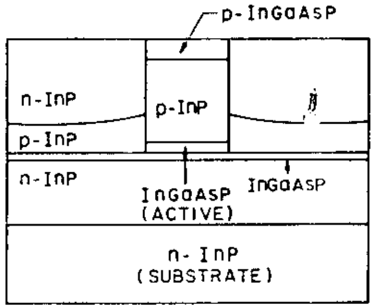
(ii)

DOUBLE CHANNEL PLANAR BURIED HETEROS

PLANAR BURIED HETEROS.



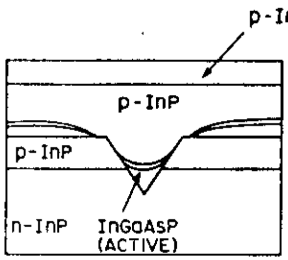
(iii)



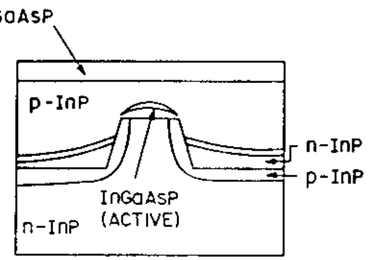
(iv)

STRIP BURIED HETEROS

CHANNELED SUBSTRATE BURIED HETEROS

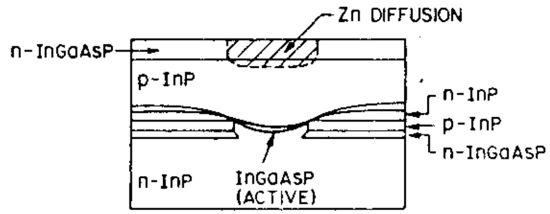


(i)



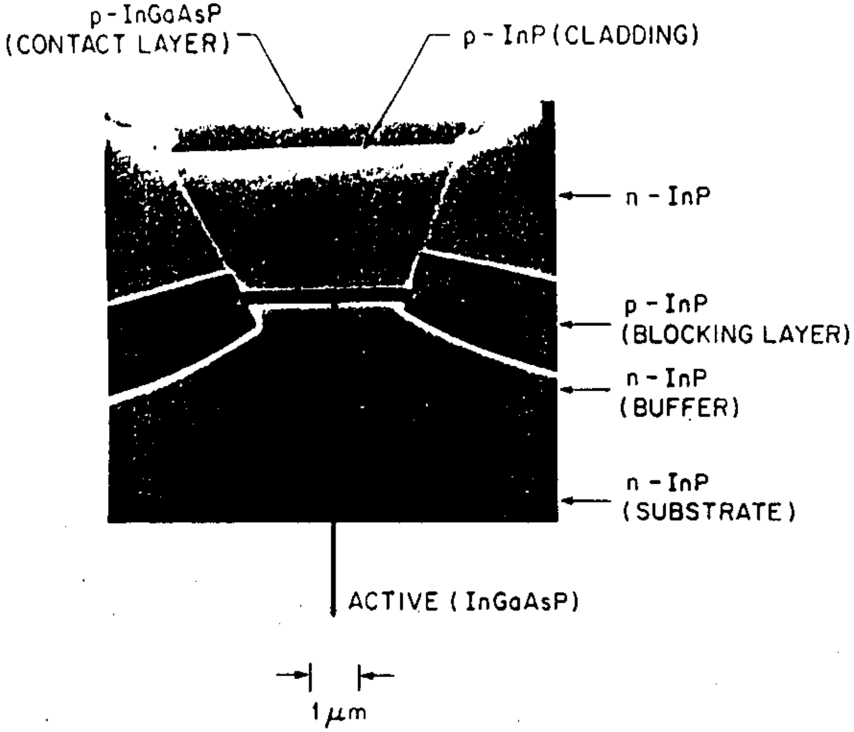
(ii)

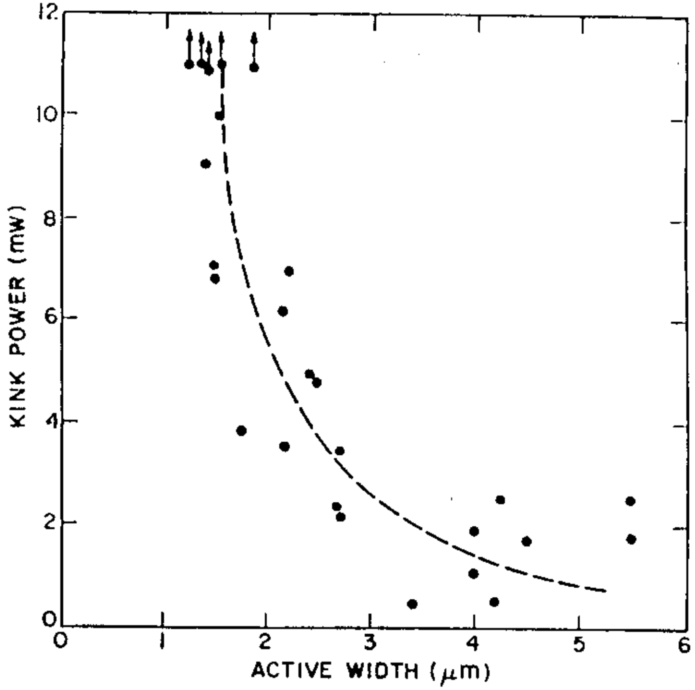
MESA SUBSTRATE BURIED HETEROS.



(iii)

BURIED CRESCENT





ADVANTAGES

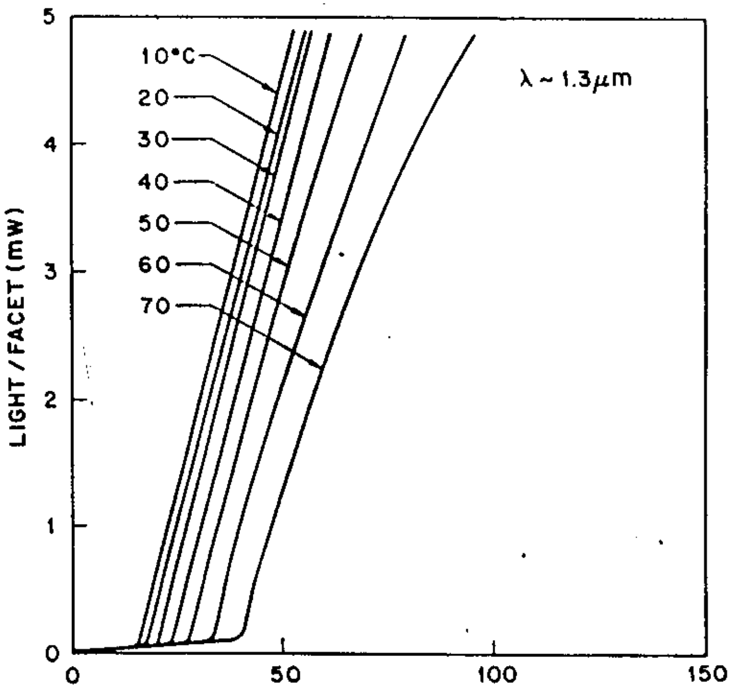
STABLE CONFINEMENT OF THE FIELD AT ANY POWER

LOW THRESHOLD CURRENT

HIGH MODULATION BANDWIDTH

DISADVANTAGES

TECHNOLOGICAL COMPLEXITY



ICTP

LASER ARRAYS

POWER LIMITATION OF SINGLE STRIPE SEMICONDUCTOR LASERS

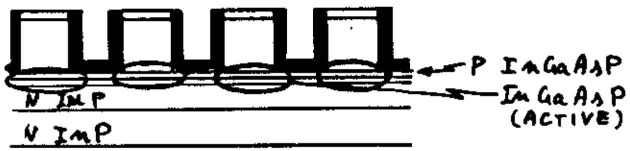
- LEAKAGE CURRENT (MAINLY InGaAs LASERS)
- FACET DAMAGE (MAINLY GaAlAs LASERS)

SOLUTION OF THE PROBLEM

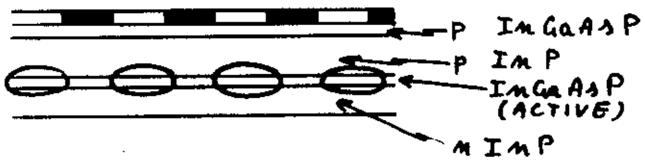
CLOSELY SPACED COUPLED MULTIPLE ACTIVE REGIONS (PHASE LOCKED ARRAYS)

FOR N COUPLED STRIPES ONE HAS A COHERENT FIELD WITH $P_{tot} \simeq NP$

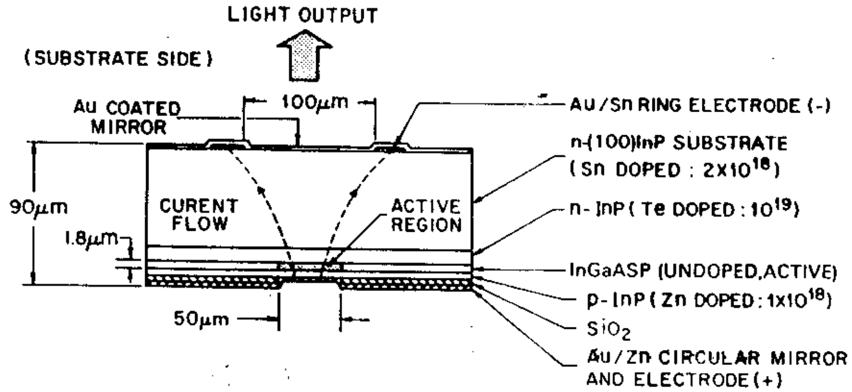
INDEX GUIDED

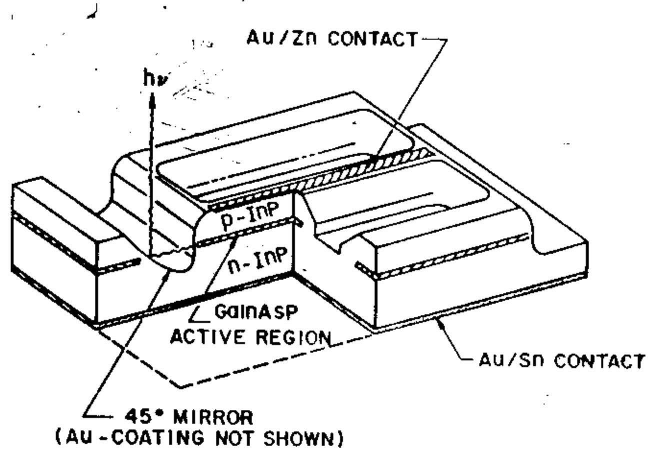


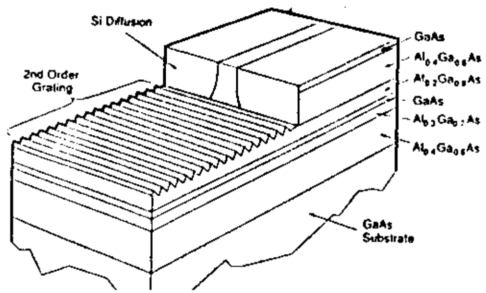
GAIN GUIDED

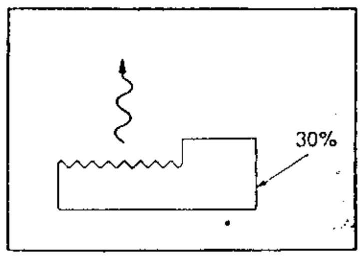


SURFACE EMITTING LASERS





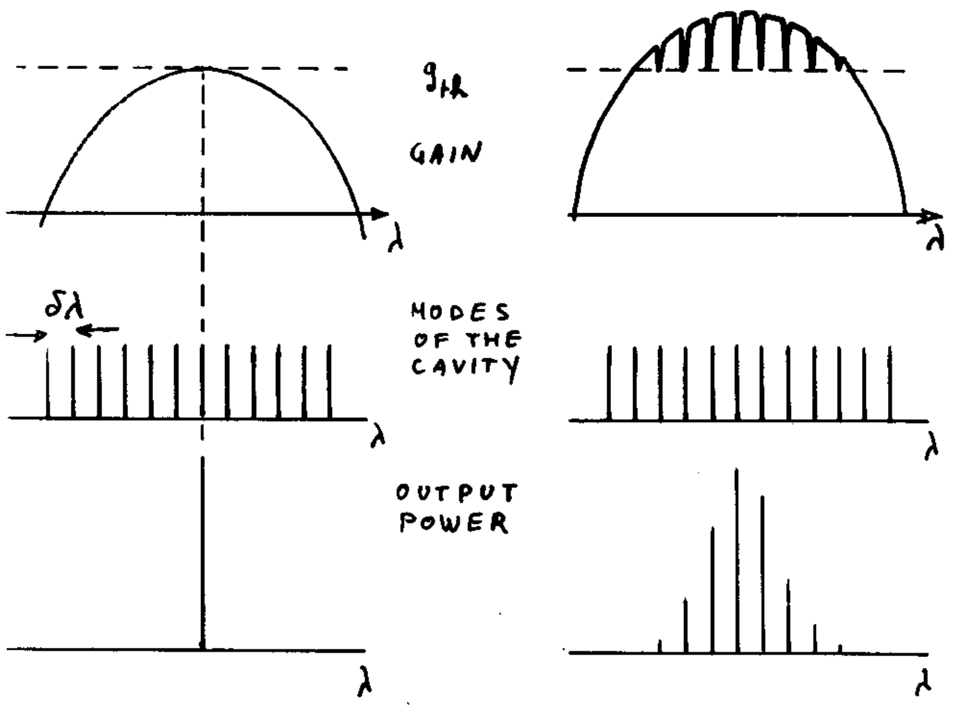




SPECTRUM OF FABRY-PEROT SEMICONDUCTOR LASERS

HOMOGENEOUS BROADENING OF THE SPECTRUM — INHOMOGENEOUS BROADENING

INDISTINGUISHABLE PARTICLES — DISTINGUISHABLE PART. (DOPPLER BROADENING)



SINGLE MODE SPECTRUM — MULTIMODE SPECTRUM

$$q\lambda_q = 2\bar{n}L$$

$$\delta\lambda = \frac{\lambda_0^2}{2\bar{n}L\left[1-(\lambda_0/\bar{n})(d\bar{n}/d\lambda)\right]}$$

SEMICONDUCTOR LASERS HAVE A MULTIMODE SPECTRUM THOUGH IT IS HOMOGENEOUSLY BROADENED

$$\frac{dI_0}{dz} = (g_0-\bar{\alpha})I_0$$

$$\downarrow$$

$$\frac{dI_0}{dz} = (g_0-\bar{\alpha})I_0 + \frac{W_{sp}}{2V}$$

g_0 = GAIN OF THE MODE CLOSEST TO THE MAXIMUM OF THE GAIN CURVE

W_{sp} = CONTRIBUTION OF THE SPONTANEOUS EMISSION TO THE LASING MODE

V = VOLUME OF THE ACTIVE MEDIUM

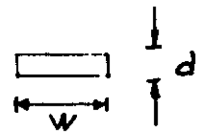
THE TERM 2 ACCOUNTS FOR THE TWO PROPAGATION DIRECTIONS

$$I_0(z) = I_0' \exp[(g_0-\bar{\alpha})z] - \frac{W_{sp}}{2V(g_0-\bar{\alpha})}$$

THE OSCILLATION CONDITION

$$I_0(0) = I_0(2L)R^2 \qquad (R_1 = R_2 = R)$$

$$P_0 = I_0(0)\frac{1-R}{R}\times d\times w$$



$$P_n = \frac{W_{sp}}{2}\,\frac{1-R\left\{\exp[(g_0-\bar{\alpha})L]-1\right\}}{(g_0-\bar{\alpha})L\left\{1-R\exp[(g_0-\bar{\alpha})L]\right\}}$$

IF THE GAIN OF THE GENERIC MODE m IS $g_m < g_0$

$$P_m = \frac{W_{sp}}{2} \frac{(1-R)\{\exp[(g_m-\bar{\alpha})L]-1\}}{(g_m-\bar{\alpha})L\{1-R\exp[(g_m-\bar{\alpha})L]\}}$$

IF $W_{sp} \to 0 \Rightarrow P_0 \neq 0$ IF $g_0 \to \frac{1}{L}\ln\frac{1}{R}+\bar{\alpha} = g_{th}$

IN THESE CONDITIONS $g_m < g_{th} \Rightarrow P_m \to 0$

IF $\varepsilon = \frac{g_{th}-g_0}{g_{th}} \ll 1$ AND $g_m = g_0\left[1-\left(\frac{m}{M}\right)^2\right]$

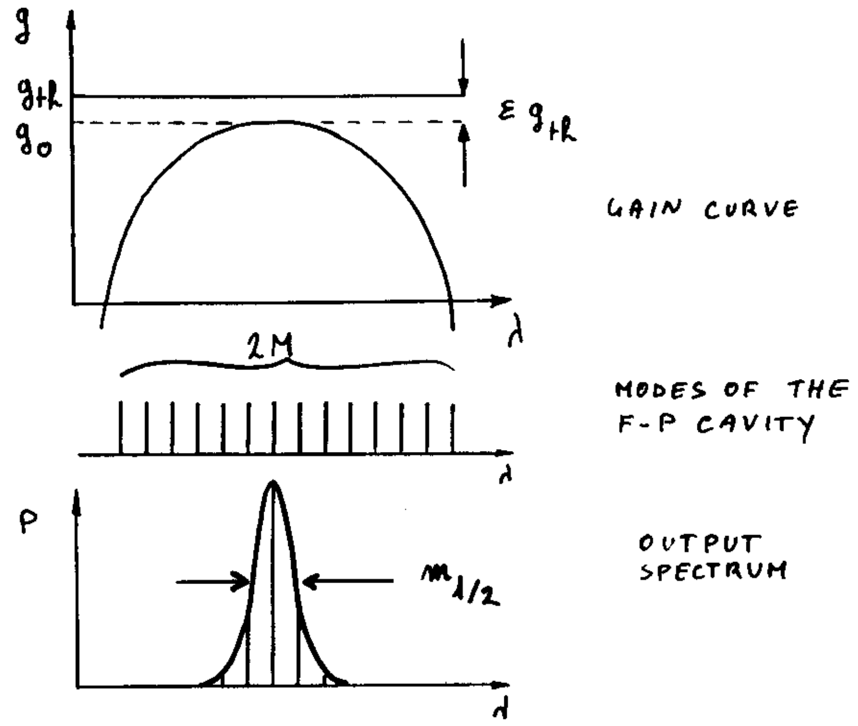
FOR $m \ll M$

$$\Downarrow$$

$$P_m \simeq \frac{W_{sp}(1-R)^2}{R\ln\frac{1}{R}\left[\varepsilon+\left(\frac{m}{M}\right)^2\right]} = P_0\frac{1}{1+\frac{(m/M)^2}{\varepsilon}}$$

THE NUMBER OF MODES WITH INTENSITIES HIGHER THAN 1/2 OF THE MAIN MODE INTENSITY

$$m_{1/2} = 2M\,\varepsilon^{1/2}$$



EXPEDIENTS TO REDUCE THE FULL WIDTH AT HALF MAXIMUM OF THE SPECTRUM $m_{1/2} = 2M\,\varepsilon^{1/2}$

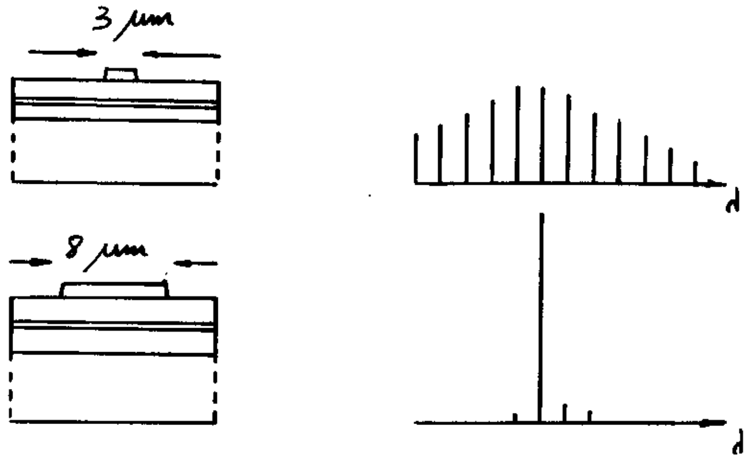
1) DECREASE OF ε $\longrightarrow$ DECREASE OF THE RATIO BETWEEN W_{sp} AND P_0

- IMPROVING THE LASER DESIGN TO REDUCE THE THRESHOLD GAIN AND CONSEQUENTLY THE CARRIER DENSITY AT THRESHOLD
- OPERATING AT HIGH EMISSION POWER

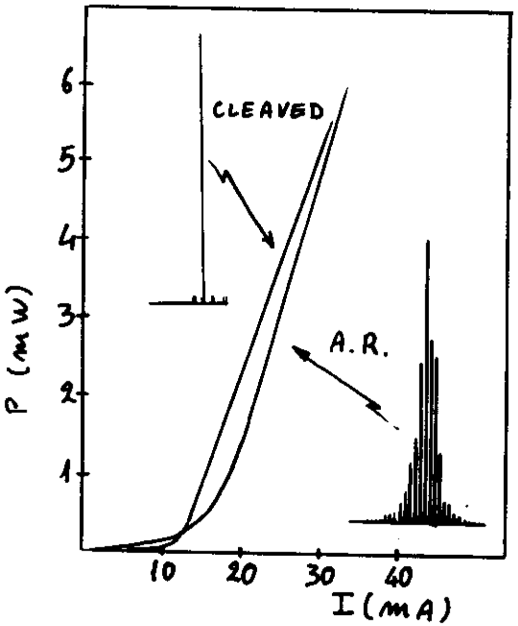
2) DECREASE OF M

- SHORT CAVITIES

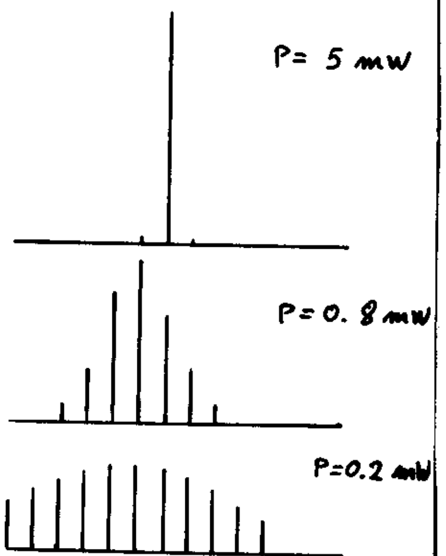
3) USE OF STRUCTURES DIFFERENT FROM SIMPLE F-P IN WHICH $R = R(\lambda)$ IS SUCH THAT $g \gg g$.



EFFECT OF LATERAL CONFINEMENT OF THE FIELD

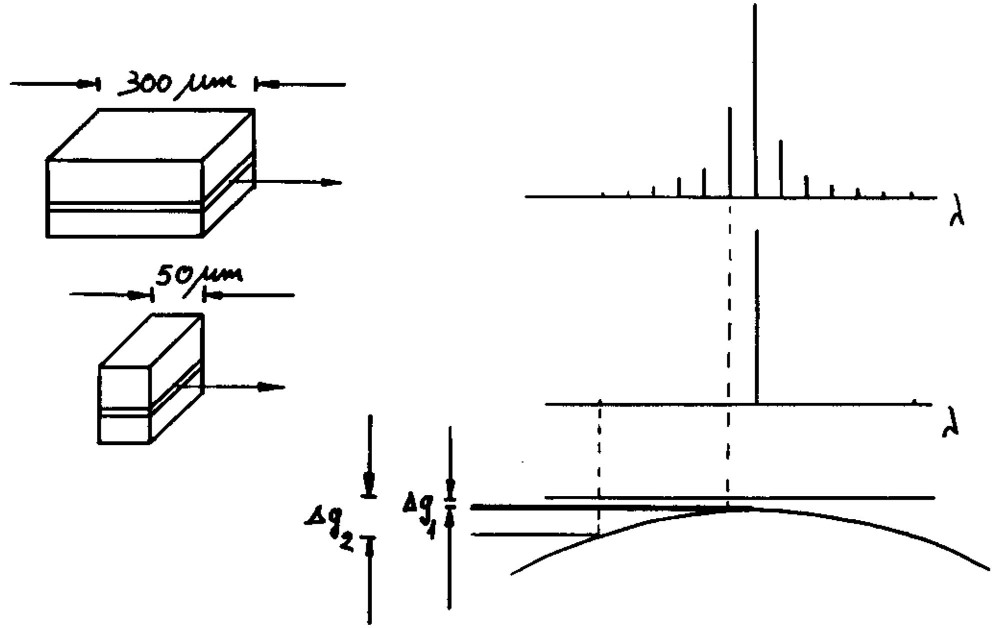


EFFECT OF THE MIRROR REFLECTIVITY



EFFECT OF THE OUTPUT POWER

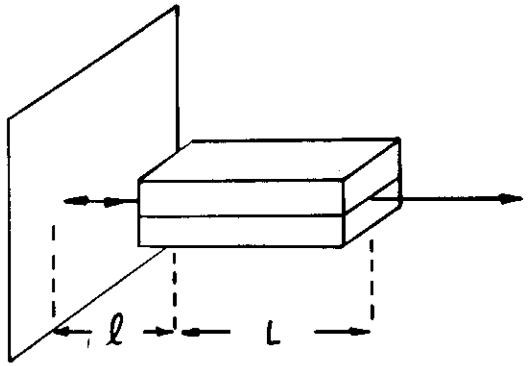
2) DECREASE OF M



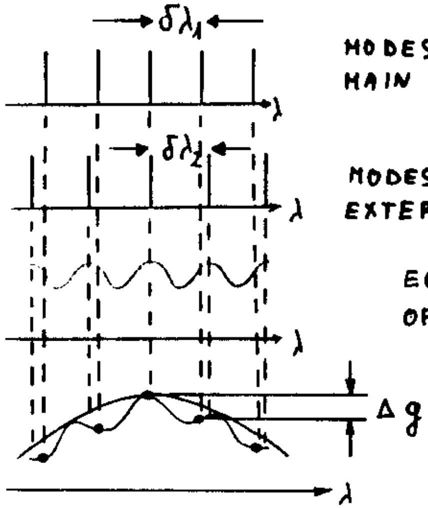
DISADVANTAGE - RELIABILITY OF THE DEVICES

3) INCREASE OF THE GAIN DIFFERENCE AMONG THE VARIOUS MODES USING WAVELENGTH DEPENDENT FEEDBACK

a) EXTERNAL CAVITIES



$$\ell \approx \bar{n} L$$



MODES OF THE MAIN CAVITY $\delta\lambda_1 = \dfrac{\lambda^2}{2\bar{n}L[1-(\lambda/\bar{n})(d\bar{n}/d\lambda)]}$

MODES OF THE EXTERNAL CAVITY $\delta\lambda_2 = \dfrac{\lambda^2}{2\ell}$

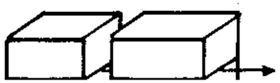
EQUIVALENT REFLECTIVITY OF THE LEFT MIRROR

GAIN CURVE

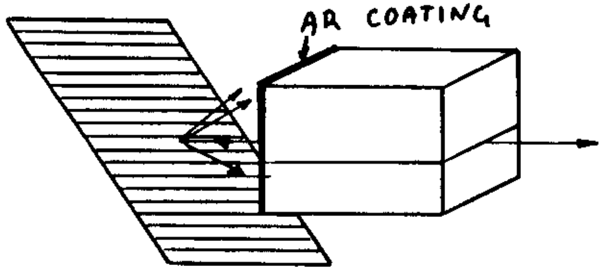
FURTHER IMPROVEMENTS

GRIN ROD REFLECTOR

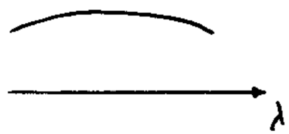
CLEAVED COUPLED CAVITY LASER



b) DISPERSIVE EXTENDED CAVITY



EQUIVALENT REFLECTIVITY OF THE LEFT MIRROR



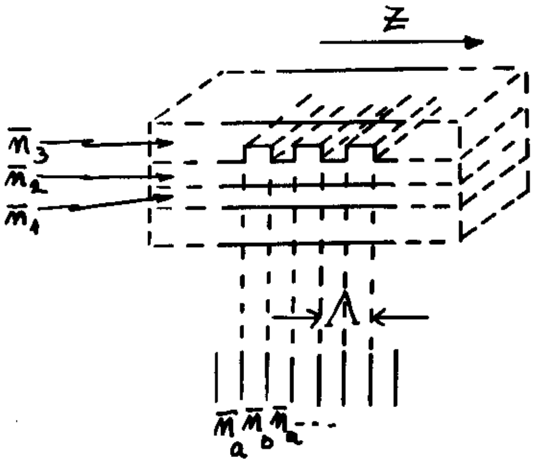
GAIN

THIS METHOD ALLOWS HIGH VALUES OF SIDE MODE SUPPRESSION RATIO (>30 dB) WITH A LARGE WAVELENGTH TUNING (100 nm)

PROBLEMS :

MECHANICAL COMPEXITY

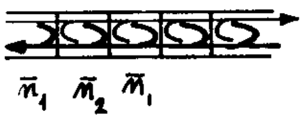
c) DISTRIBUTED FEEDBACK LASERS
DISTRIBUTED BRAGG REFLECTOR LASERS



Λ = GRATING PERIOD

BASIC CONCEPTS

REFLECTION AT THE PASSAGE BETWEEN TWO REGIONS WITH DIFFERENT REFRACTIVE INDEX



ROUGHLY SPEAKING THE DFB LASER IS EQUIVALENT TO A SYSTEM WITH A SERIES OF VERY SMALL REFLECTIONS AT THE DISCONTINUITY INTERFACES. A COUPLING BETWEEN FORWARD AND BACKWARD WAVES (EQUIVALENT TO CONCENTRATE REFLECTIONS IN F-P LASERS) IS POSSIBLE ONLY FOR THOSE WAVELENGTHS WHICH, AFTER ANY REFLECTION, ADD IN PHASE WITH THE PRE-EXISTENT FIELD.

$$\nabla^2 \underline{\mathcal{E}} + \varepsilon(x,y,z)\, k_0^2\, \underline{\mathcal{E}} = 0$$

$$\varepsilon(x,y,z) = \bar{\varepsilon}(x,y) + \Delta\varepsilon(x,y,z) =$$

$$= \bar{\varepsilon}(x,y) + \sum_{\ell \neq 0} \Delta\varepsilon_\ell(x,y)\, \exp\left[i\left(\frac{2\pi}{\Lambda}\right)\ell z\right]$$

FOR $\Delta\varepsilon = 0$

$$\mathcal{E} = \hat{y}\, U(x,y)\left[\mathcal{E}_f \exp(i\beta z) + \mathcal{E}_b \exp(-i\beta z)\right]$$

WHERE $U(x,y)$ IS THE SOLUTION OF

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \left[\bar{\varepsilon}(x,y)\, k_0^2 - \beta^2\right] U = 0$$

$$\beta = \bar{n}\, k_0 - i\, \frac{\Gamma g - \bar{\alpha}}{2}$$

SUBSTITUTING $\mathcal{E}$ IN THE WAVE EQUATION AND ALLOWING FOR SLOW AXIAL VARIATIONS OF $\mathcal{E}_f$ AND $\mathcal{E}_b$

$$\frac{d\mathcal{E}_f}{dz} \exp(i\beta z) - \frac{d\mathcal{E}_b}{dz} \exp(-i\beta z) =$$

$$= i\, \frac{k_0^2}{2\beta}\, \frac{\iint \Delta\varepsilon(x,y,z)\, U^2(x,y)\, dx\, dy}{\iint U^2(x,y)\, dx\, dy} \times$$

$$\times \left[\mathcal{E}_f \exp(i\beta z) + \mathcal{E}_b \exp(-i\beta z)\right]$$

- COLLECTING ONLY THE TERMS APPROXIMATELY PHASE-MATCHED

$$\frac{d\mathcal{E}_f}{dz} = i\,\kappa\,\mathcal{E}_b \exp(-2i\Delta\beta z)$$

$$\frac{d\mathcal{E}_b}{dz} = -i\,\kappa^*\,\mathcal{E}_f \exp(2i\Delta\beta z)$$

$\Delta\beta = \beta - \frac{m\pi}{\Lambda} = \beta - \beta_0$ IS THE SMALLEST FOR $\ell = m$

$$\kappa = \frac{k_0^2}{2\beta}\,\frac{\iint \Delta\varepsilon_m(x,y)\,U^2(x,y)\,dx\,dy}{\iint U^2(x,y)\,dx\,dy}$$

IS THE COUPLING FACTOR - REAL IN INDEX GUIDED LASERS

USING $\beta_0 = \frac{m\pi}{\Lambda}$ INSTEAD OF THE PROPAGATION CONSTANT

$$\mathcal{E}(z) = A(z)\exp(i\beta_0 z) + B(z)\exp(-i\beta_0 z)$$

$$A = \mathcal{E}_f \exp(i\Delta\beta z)$$

$$B = \mathcal{E}_b \exp(-i\Delta\beta z)$$

THE COUPLED DIFFERENTIAL WAVE-EQUATIONS BECOME

$$\frac{dA}{dz} = i\Delta\beta A + i\kappa B$$

$$-\frac{dB}{dz} = i\Delta\beta B + i\kappa A$$

WHOSE SOLUTION IS

$$A(z) = A_1\exp(iqz) + A_2\exp(-iqz)$$

$$B(z) = B_1\exp(iqz) + B_2\exp(-iqz)$$

WITH A_1, B_1 AND A_2, B_2 LINKED BY

$$(q-\Delta\beta)A_1 = \kappa B_1$$

$$(q+\Delta\beta)B_1 = -\kappa A_1$$

$$(q-\Delta\beta)B_2 = \kappa A_2$$

$$(q+\Delta\beta)A_2 = -\kappa B_2$$

$$q = \pm\left[(\Delta\beta)^2 - \kappa^2\right]^{1/2}$$

$\Downarrow$

$$A(z) = A_1\exp(iqz) + r(q)\,B_2\exp(-iqz)$$

$$r(q) = \frac{q - \Delta\beta}{\kappa} = -\frac{\kappa}{q+\Delta\beta} \leqslant 1$$

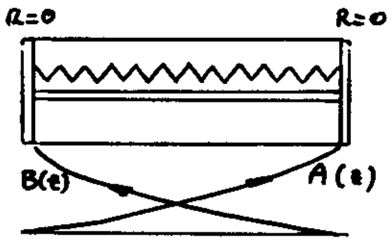
BY THE CONDITION

$$q = \pm\left[(\Delta\beta)^2 - \kappa^2\right]^{1/2}$$

$$\Downarrow$$

$$|\Delta\beta| > \kappa \qquad \beta < \beta_0 - \kappa \qquad \beta > \beta_0 + \kappa$$

BOUNDARY CONDITIONS FOR A PERFECT ANTIREFLECTION COATED DFB



$$\begin{cases} A(0) = 0 \\ B(L) = 0 \end{cases}$$

$$\Downarrow$$

$$\boxed{r^2(q)\,\exp(2iqL) = 1}$$

THIS RELATION IS EQUIVALENT TO THE THRESHOLD CONDITION FOR F-P LASERS

THE EIGENVALUES q CAN BE OBTAINED SOLVING THIS EQUATION

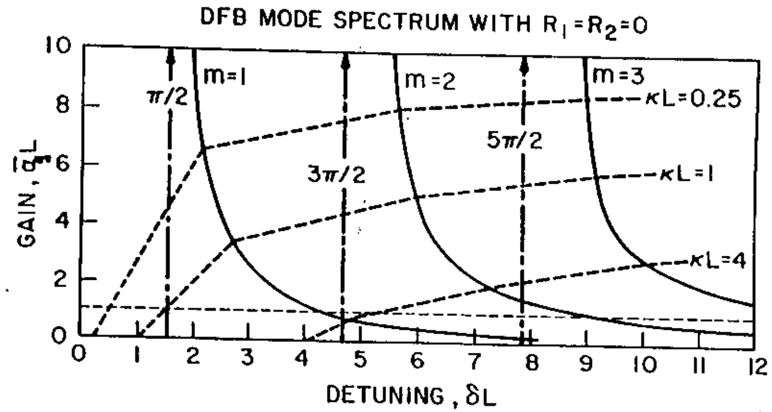
ONCE THIS HAS BEEN DONE ONE CAN EVALUATE

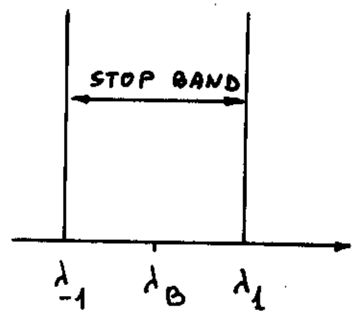
$$\Delta\beta = \pm(q^2 + \kappa^2)^{1/2}$$

$$\Delta\beta = \delta - i\,\frac{\bar{\alpha}_g}{2}$$

$$\delta = \bar{n}k_0 - \beta_0 = -\frac{2\pi\bar{n}}{\lambda^2}\left[1 - \frac{\lambda}{\bar{n}}\left(\frac{dn}{d\lambda}\right)\right]\Delta\lambda$$

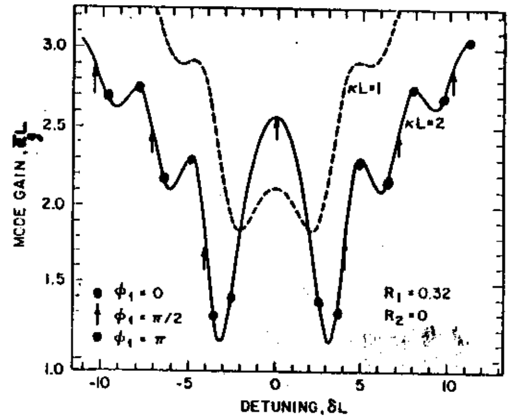
$$g_{th} = \Gamma g = \bar{\alpha}_g + \bar{\alpha}$$

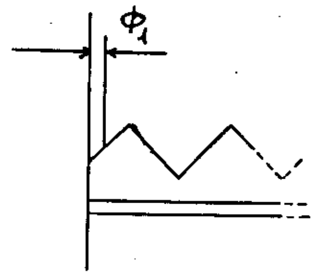




OUTPUT SPECTRUM

THE DOUBLE PEAKED SPECTRUM CAN BE REDUCED TO A SINGLE MODE SPECTRUM BY USING ONE REFLECTING FACET

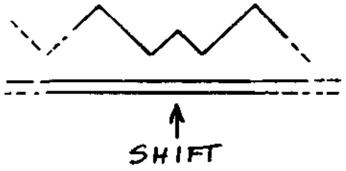




DISADVANTAGES:

RANDOM POSITION OF CLEAVING $\Rightarrow$ RANDOM VALUE OF ϕ_1

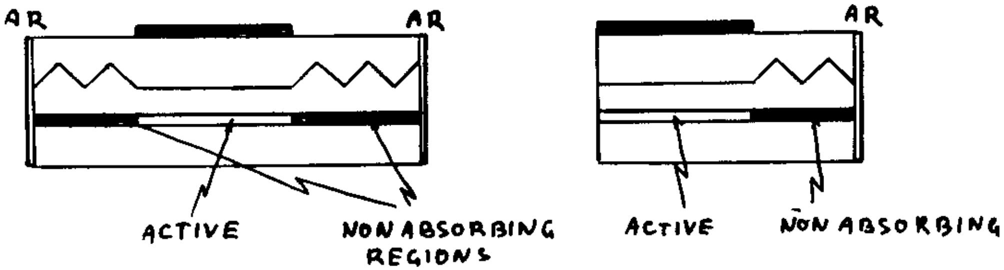
THE TWO PEAKS CAN BE REMOVED ALSO USING A $\lambda/4$ SHIFT IN THE GRATING AND AR COATING ON THE FACETS



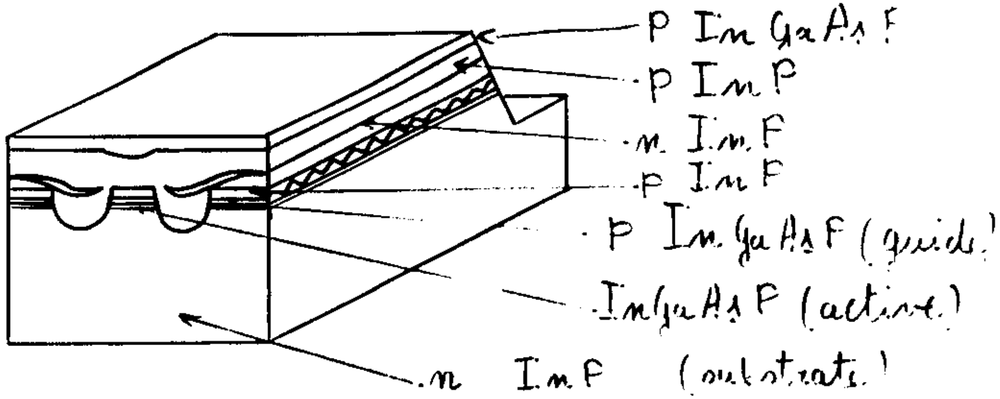
ADVANTAGES: VERY HIGH SIDE MODE SUPPRESSION RATIO (>30 dB)

DISADVANTAGES: VERY COMPLICATED TECHNOLOGY
SENSITIVITY TO EXTERNAL DISTURBANCES

DBR LASERS

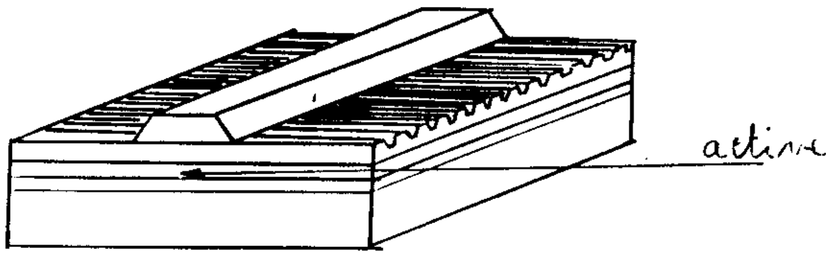


SIMILAR TO F-P LASERS, BUT WITH ONE OR BOTH MIRRORS SUBSTITUTED BY FREQUENCY DEPENDENT MIRRORS



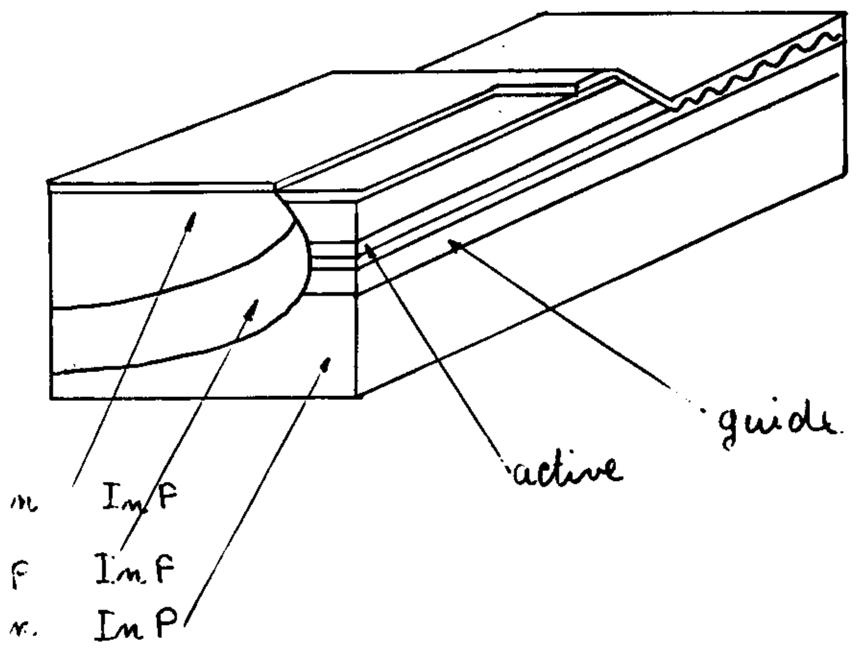
distributed feedback - double channel - planar buried heterostructure laser diode

DFB-DC-PBH LD



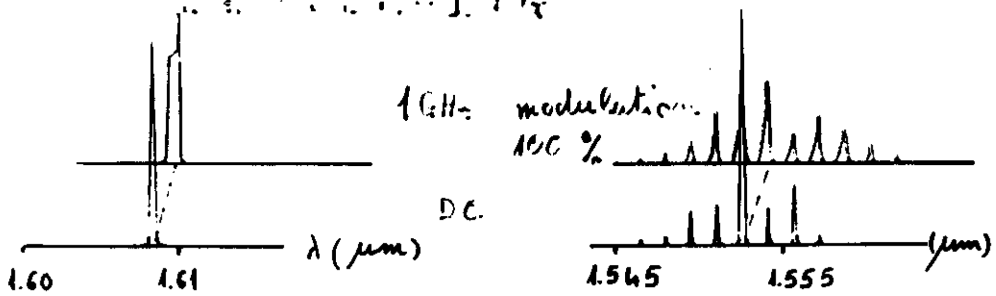
ridge waveguide DFB

Cross section DBR



Buried Heterostructure Integrated Twin Guide [illegible] with Bragg Reflector

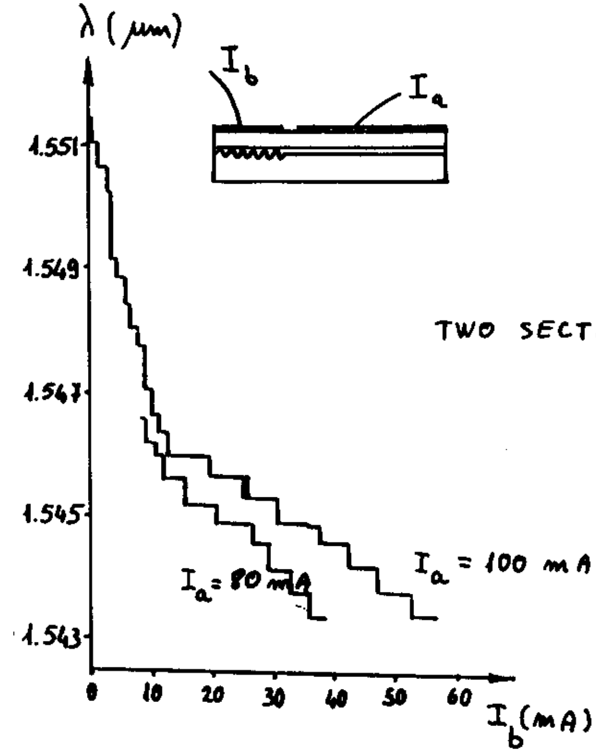
[illegible] ITG



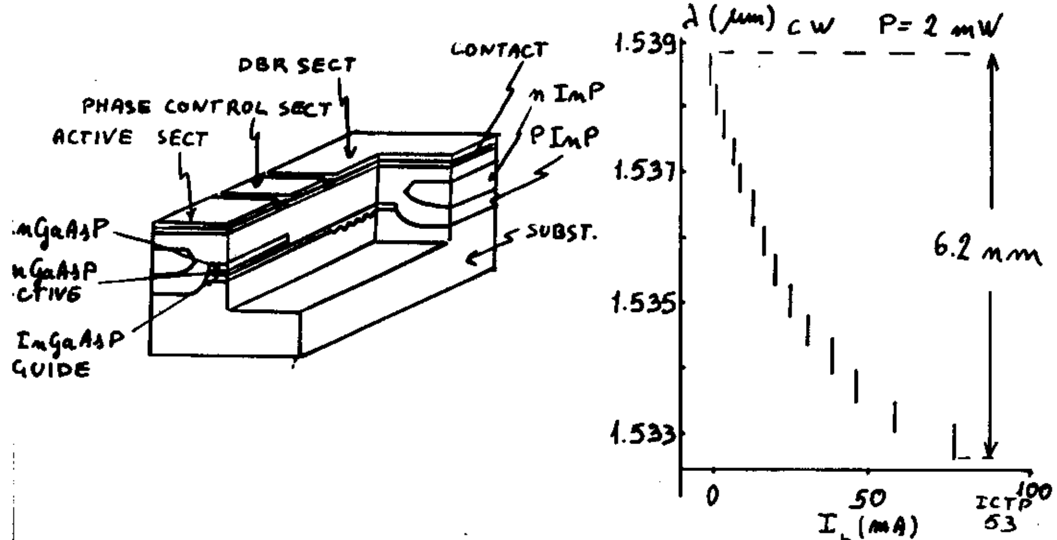
DBR

FP

IMPROVEMENTS: MULTI-SECTION DFB-DBR LASERS



THREE SECTIONS



MODULATION OF SEMICONDUCTOR LASERS

RATE EQUATION FORMULATION

$$\frac{dN}{dt} = \frac{J}{ed} - A(N-N_0)N_{pR} - \frac{N}{\tau_s}$$

$$\frac{dN_{pR}}{dt} = A(N-N_0)N_{pR} - \frac{N_{pR}}{\tau_{pR}} + \gamma\frac{N}{\tau_s}$$

APPROXIMATIONS:

- SINGLE MODE LASER
- HOMOGENEOUS POPULATION INVERSION IN AN ACTIVE LAYER HAVING A THICKNESS d
- NO LATERAL DIFFUSION OF CARRIERS (BH LASER)
- GAIN PROPORTIONAL TO CARRIER DENSITY
- $\Gamma = 1$
- ADIABATIC ELIMINATION OF POLARIZATION
- <u>CONSTANT CARRIER LIFETIME</u>

SYMBOLS

N_0 CARRIER DENSITY AT TRANSPARENCY

τ_s SPONTANEOUS CARRIER LIFETIME (~ 1 ns)

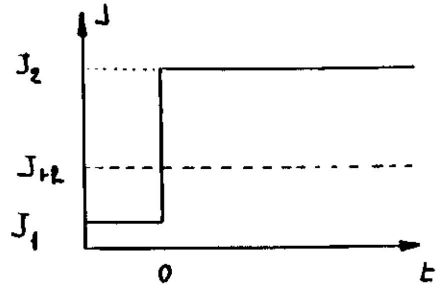
$$\tau_{pR} = \frac{\bar{n}\left[1 - \frac{\lambda}{\bar{n}}\frac{d\bar{n}}{d\lambda}\right]}{c\left(\bar{\alpha} + \frac{1}{2L}\ln\frac{1}{R_1R_2}\right)}$$ (~ 2-5 ps) PHOTON LIFETIME

γ PERCENTAGE OF SPONTANEOUSLY EMITTED PHOTONS COUPLED TO THE LASING MODE

PULSE RESPONSE

$J = J_1 < J_{th}$ $\quad t \leq 0$

$J = J_2 > J_{th}$ $\quad t > 0$



FIRST STAGE

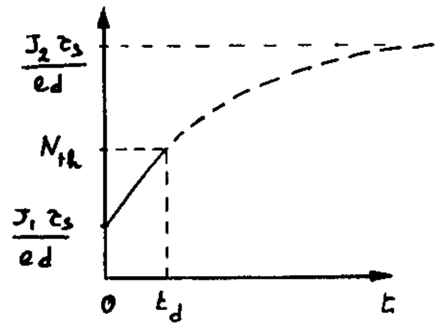
$N < N_{th} = \frac{J_{th}\tau_s}{ed} \Rightarrow g < g_{th}$

$N_{pR} \sim 0$

$$\frac{dN}{dt} = \frac{J}{ed} - \frac{N}{\tau_s}$$

$$\Downarrow$$

$$N = \frac{J_2}{ed}\tau_s - \frac{J_2 - J_1}{ed}\tau_s \exp(-t/\tau_s)$$



THE FIRST STAGE LASTS t_d

$$t_d = \tau_s \ln\frac{J_2 - J_{th}}{J_2 - J_1}$$

SECOND STAGE

$N \geq N_{th}$ $\quad N_{pR} \neq 0$

ANALYTICAL SOLUTION IF <u>$\gamma = 0$</u> AND

$\Delta N = N - \bar{N} = N - N_{th} \ll N_{th}$

$\Delta N_{pR} = N_{pR} - \bar{N}_{pR} \ll \bar{N}_{pR}$

$$\Delta N = \Delta N^0 \exp\left[(-a + i\omega_c)t\right]$$

$$\Delta N_{PR} = \Delta N_{PR}^0 \exp\left[(-a + i\omega_c)t\right]$$

$$a = \frac{J_2}{2 J_{tR} \tau_s} = \frac{1}{2}\left[\frac{1}{\tau_s} + A \bar{N}_{PR}\right]$$

($a = \frac{1}{2}\left[\frac{1}{\tau_s} + (A + \varepsilon)\bar{N}_{PR}\right]$ IF GAIN SATURATION AT HIGH POWER IS ACCOUNTED FOR AND $A \rightarrow \frac{A}{1 + \varepsilon N_{PR}}$)

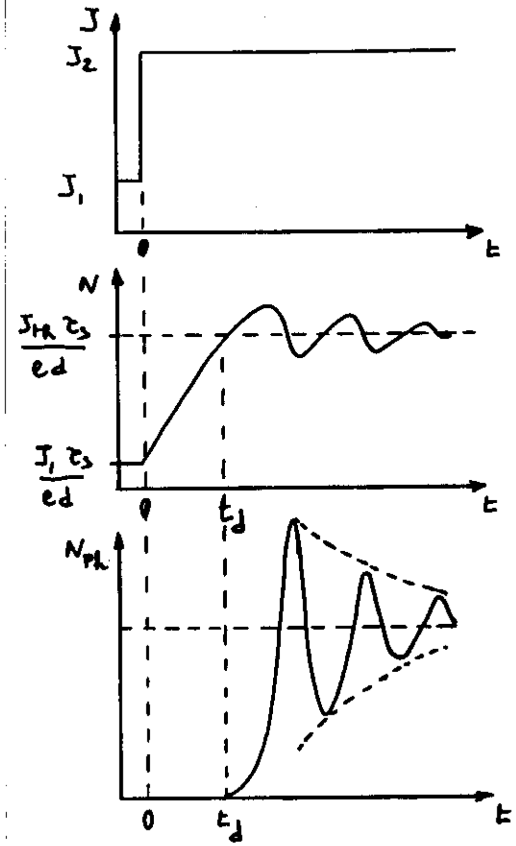
$$\omega_c = \left[\left(\frac{J_2}{J_{tR}} - 1\right)\frac{1}{\tau_s \tau_{PR}} - \frac{J_2^2}{4 J_{tR}^2 \tau_s^2}\right] \simeq \left[\left(\frac{J_2}{J_{tR}} - 1\right)\frac{1}{\tau_s \tau_{PR}}\right]^{1/2} =$$

$$= \left(\frac{A \bar{N}_{PR}}{\tau_{PR}}\right)^{1/2}$$

HIGH VALUES OF ω_c → HIGH CURRENT IN THE ON STATE J_2 (HIGH $\bar{N}_{PR}$)

LOW VALUES OF τ_{PR} (HIGH LOSSES IN THE CAVTY)

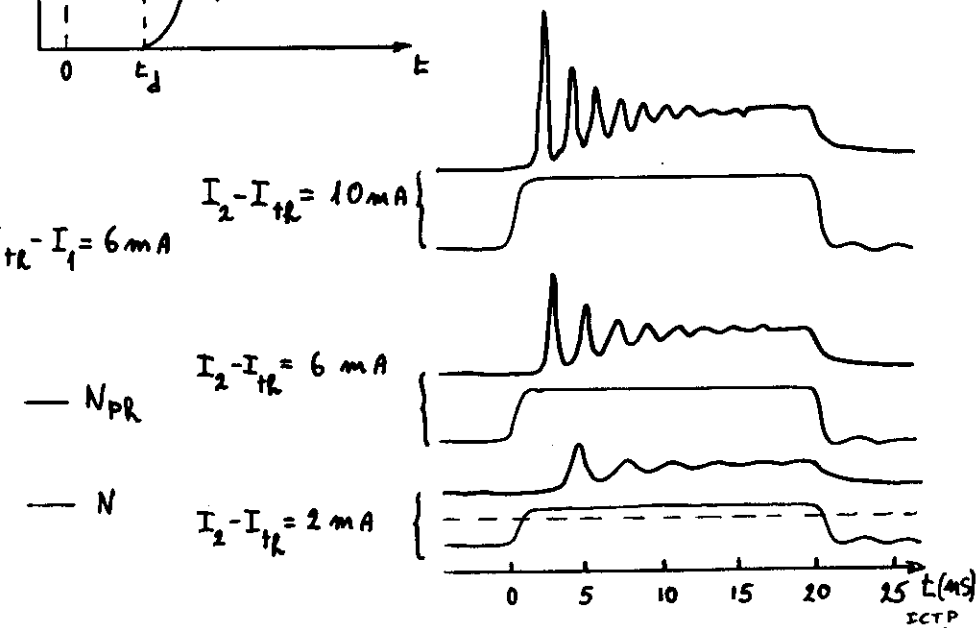
HIGH VALUE OF DIFFERENTIAL GAIN A



- SHORT OPTICAL PULSES (~10 ps)

PROBLEMS

- PATTERN EFFECT (RECOVERY TIME > ns)
- TIME JITTER (~50 ps)



FREQUENCY RESPONSE

$$J = \bar{J} + J' e^{i\omega t} \qquad J' \ll \bar{J}$$

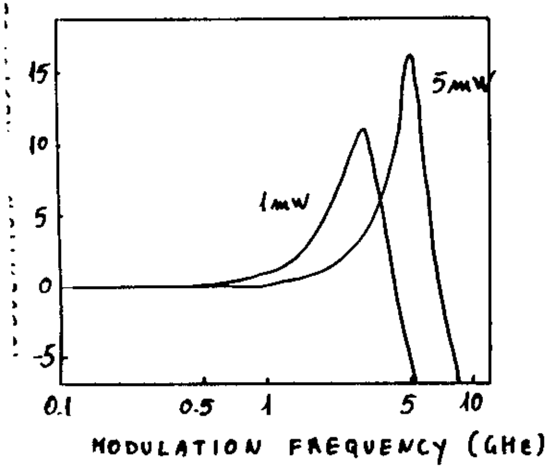
$$\Downarrow$$

$$N = \bar{N} + N' e^{i\omega t}$$

$$N_{ph} = \bar{N}_{ph} + N'_{ph} e^{i\omega t}$$

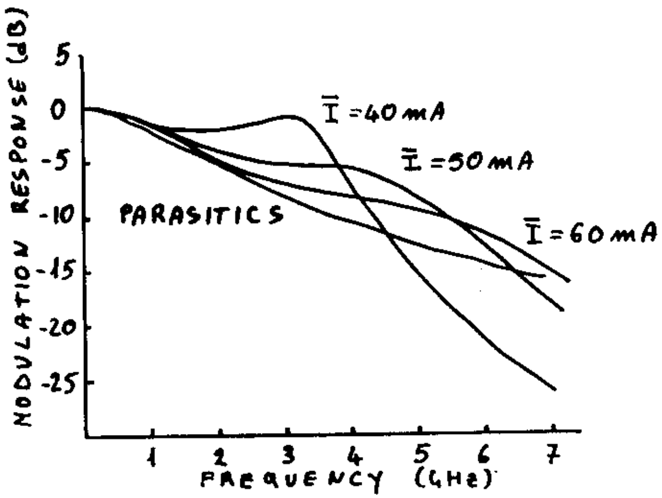
BY THE SOLUTION OF THE SET OF DIFFERENTIAL EQUATIONS

$$\left| \frac{N'_{ph}(\omega)}{J'} \right| = \frac{1}{e\, d\, \tau_{ph} \left[(\omega^2 - \omega_c)^2 - 4 a^2 \omega^2 \right]^{1/2}}$$

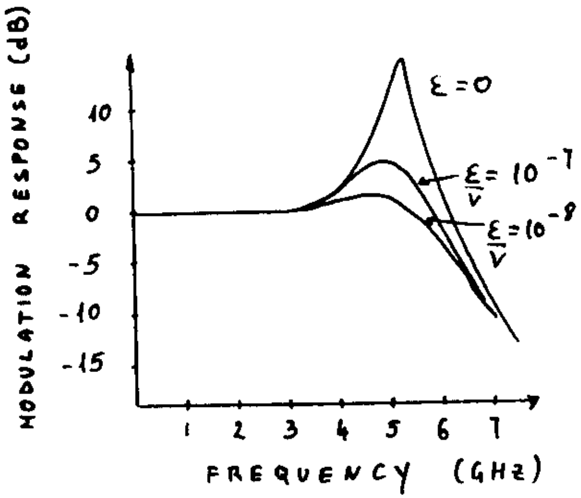


LIMITATIONS TO THE MAXIMUM MODULATION FREQUENCY

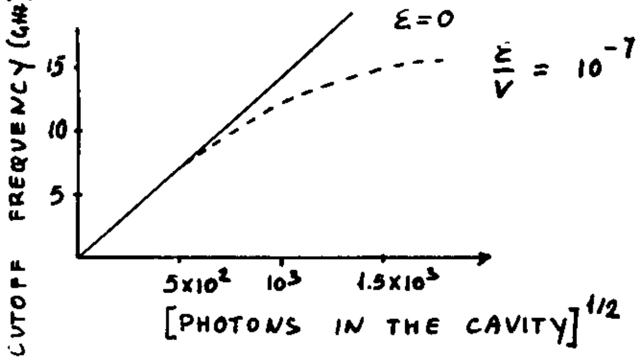
1) PARASITICS



2) NON LINEAR GAIN COEFFICIENT ε



$$\omega_{3dB}^2 = (\omega_c^2 - 2a) + \left[(\omega_c^2 - 2a)^2 + \omega_c^4\right]^{1/2}$$



MAXIMUM MODULATION FREQUENCY

20 GHz	AT	1.55 μm	MULTIMODE
17 GHz	"	"	SINGLE MODE
35 GHz	"	"	T = - 40 °C (HIGHER DIFFER. GAIN A)

FURTHER IMPROVEMENTS OF LASER DIODES

QUANTUM WELL LASERS

IN AN ORDINARY DH LASER THE KINETIC ENERGY OF THE ELECTRON IN THE CONDUCTION BAND

$$E = (\hbar^2/2m_e)(k_x^2 + k_y^2 + k_z^2)$$

IF d DECREASES TO

$$\lambda_{DB} \simeq h/p$$

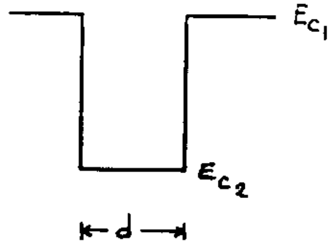
$$\Downarrow$$

QUANTIZATION OF THE KINETIC ENERGY FOR THE MOTION ALONG x

ONE DIMENSIONAL POTENTIAL WELL

SCHRÖDINGER EQUATION

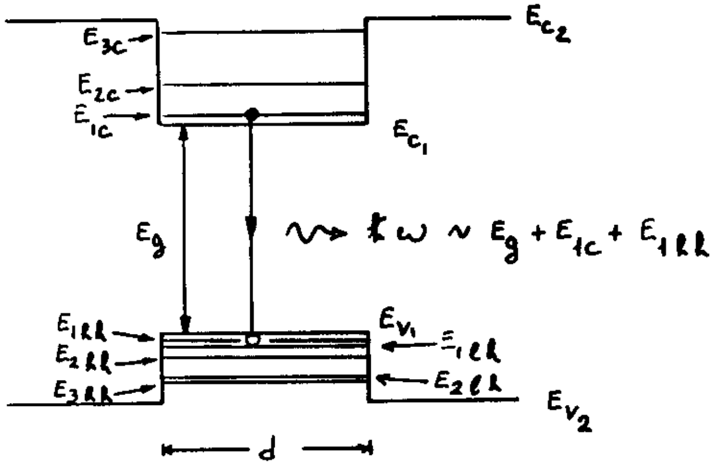
$$\begin{cases} E\psi = -\dfrac{\hbar^2}{2m_e}\dfrac{d^2\psi}{dx^2} & -\dfrac{d}{2} < x < \dfrac{d}{2} \\ E\psi = -\dfrac{\hbar^2}{2m_e}\dfrac{d^2\psi}{dx^2} + V\psi & x > \dfrac{d}{2},\; x < -\dfrac{d}{2} \end{cases}$$



$$V = (E_{c_1} - E_{c_2})/e$$

$$E_n = \frac{\hbar^2}{2 m_e} \left(\frac{n \pi}{d}\right)^2$$

$$E(n, k_x, k_y) = E_n + \frac{\hbar^2}{2 m_e} (k_x^2 + k_y^2)$$



$$\rho_{ci}(\epsilon) = \frac{m_{ei}}{\pi \hbar^2 d} \qquad QW$$

$$\rho_c(\epsilon) = 4\pi \left(\frac{2 m_e}{\hbar^2}\right)^{3/2} E^{1/2} \qquad DH$$

MAIN ADVANTAGES OF QW LASERS

- LESS SENSITIVE DEPENDENCE OF THRESHOLD CURRENT ON TEMPERATURE
- EASE CHANGE OF EMISSION WAVELENGTH (FUNCTION OF d) WITH THE SAME COMPOSITION OF ACTIVE LAYER
- LOWER THRESHOLD CURRENT
- HIGH VALUE OF DIFFERENTIAL GAIN $A = \frac{dG}{dN}$.

  THE EFFECT ON THE MAXIMUM ATTAINABLE FREQUENCY OF MODULATION IS, HOWEVER, NOT VERY STRONG BECAUSE OF A CORRESPONDING INCREASE OF GAIN SATURATION ϵ.