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

H4.SMR/453-35

TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

(5 February - 2 March 1990)

OPTICAL FIBRE SYSTEMS AND RELATED DEVICES

E. Vezzoni

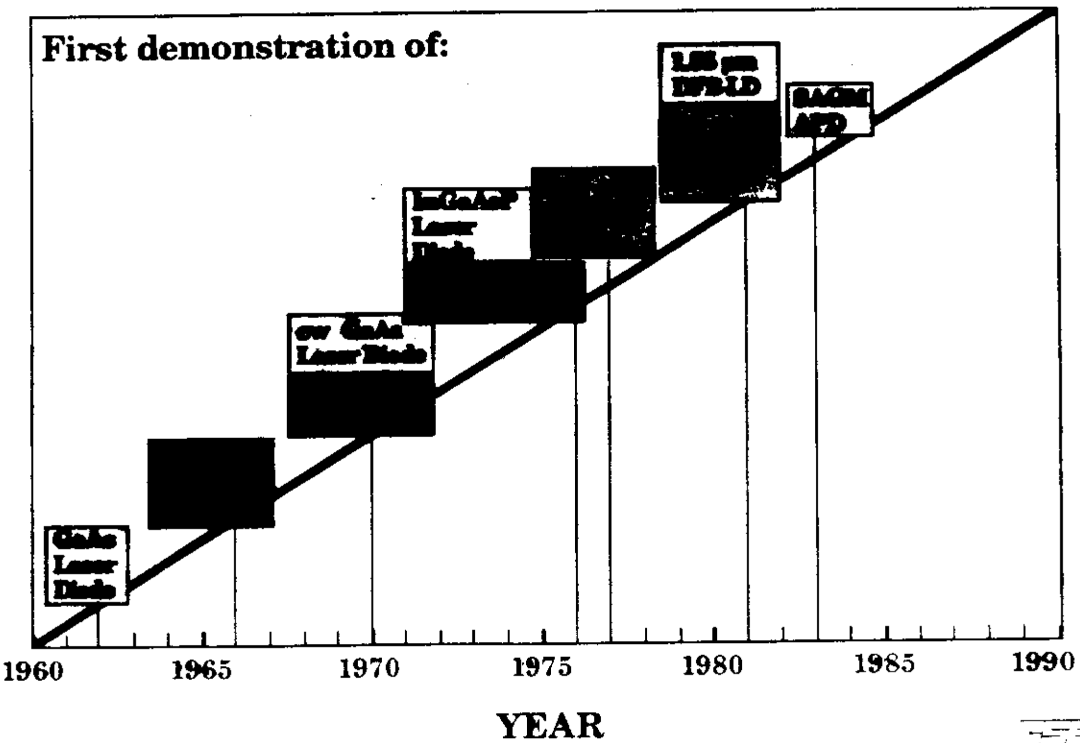
CSELT
Torino, Italy

OPTICAL FIBRE SYSTEMS AND RELATED DEVICES

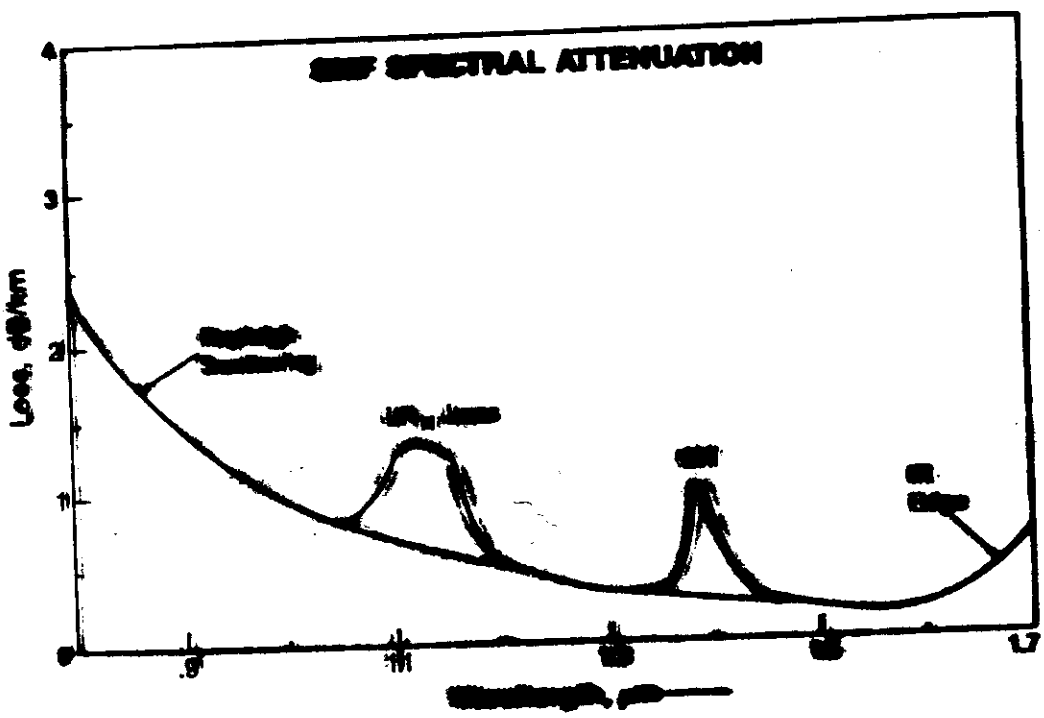
E. Vezzoni

(CSELT)

EVOLUTION OF OPTOELECTRONICS AND FIBRE TECHNOLOGY

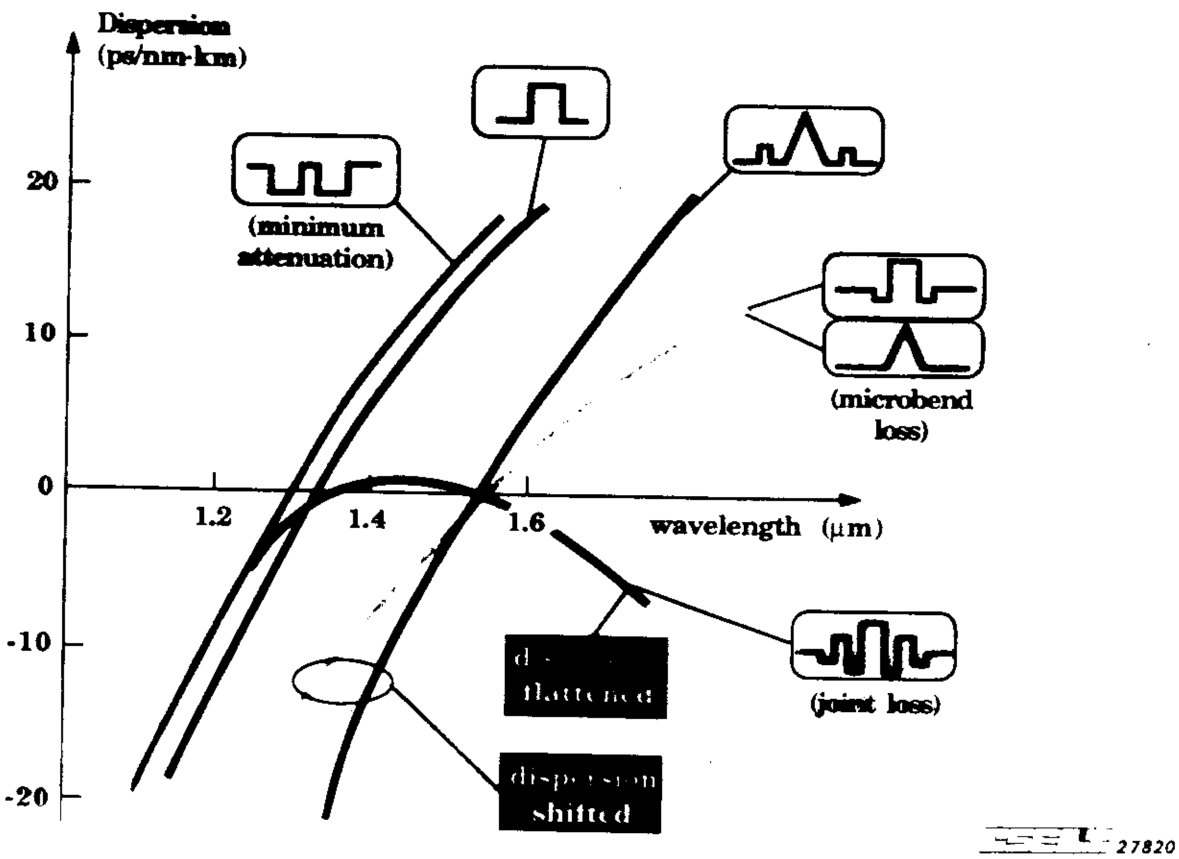


27821



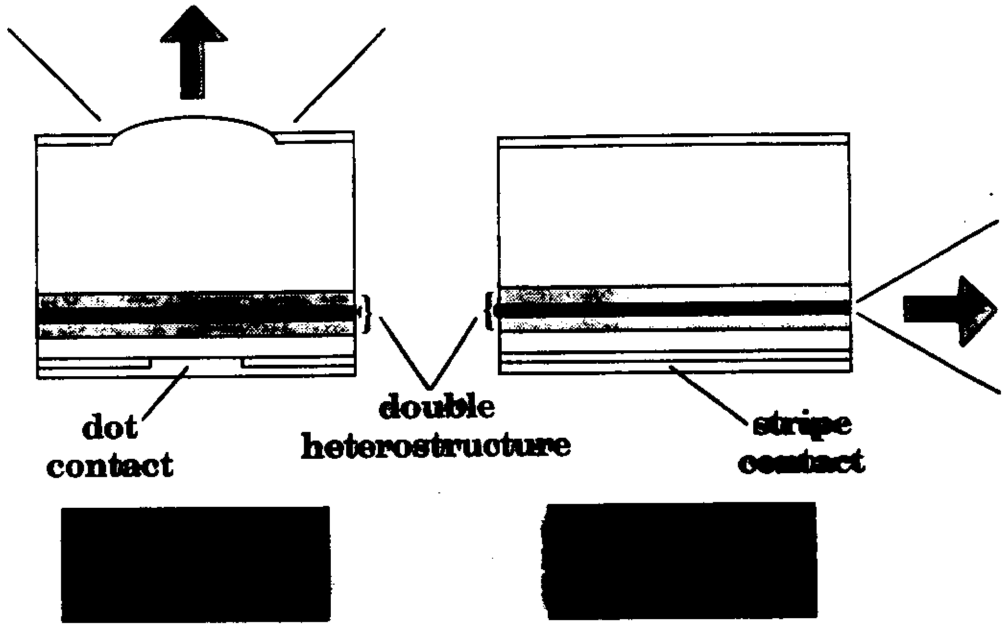
AFTER: D. FRANZEN, OFC '88

REFRACTIVE INDEX PROFILE AND CHROMATIC DISPERSION IN SINGLE MODE OPTICAL FIBRES



27820

LIGHT EMITTING DIODE (LED)



to increase coupling efficiency:

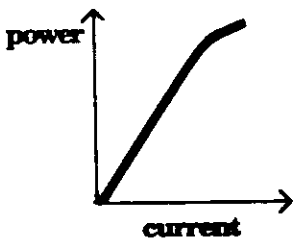
- monolithic lens

to prevent from lasing:

- AR coated facets
- truncated stripe
- thin active layer

Both AlGaAs/GaAs and InGaAsP/InP are used

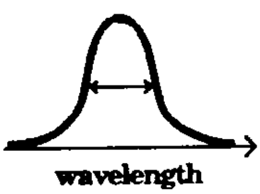
OPERATIONAL CHARACTERISTICS OF 1.3 μm LEDs



Output power:

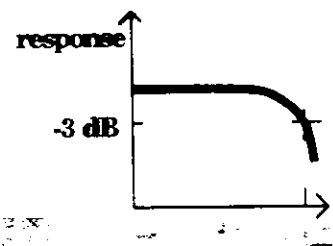
- Total: a few mW
- Into MM fibre: 10 ÷ 100 μW
- Into SM fibre : ~ 10 μW (edge)
  ~ 1 μW (surface)

Bias current: 100 ÷ 200 mA



Spectral width (FWHM):

- ~70 nm (edge emitters)
- ~120 nm (surface emitters)

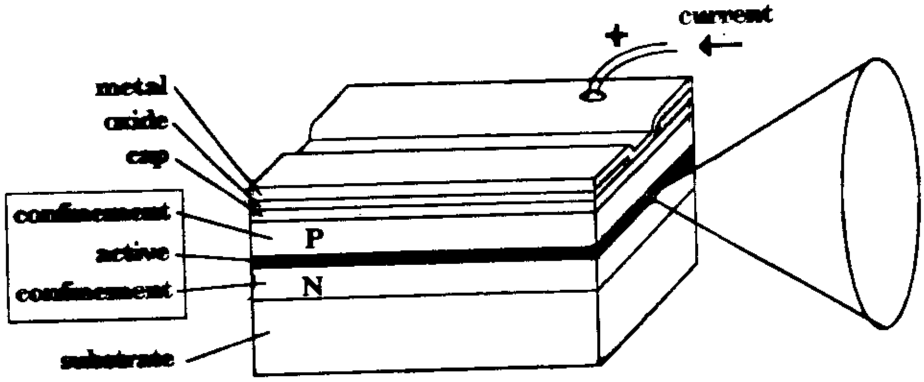


Bandwidth:

- 20 ÷ 200 MHz:
  bandwidth/power trade-off

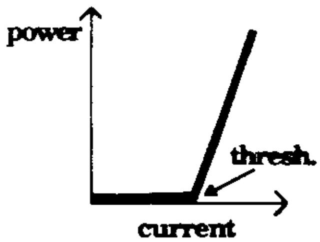
27815

LASER DIODE



- Double heterostructure, stripe geometry
- Cleaved mirrors (Fabry-Perot resonator)
- AlGaAs/GaAs for 0.85 μm operation
  InGaAsP/InP for 1.3 - 1.55 μm operation
- Epitaxial growth: LPE, MO-CVD, MBE, ...

OPERATIONAL CHARACTERISTICS OF 1.3 ÷ 1.55 μm LASER DIODES

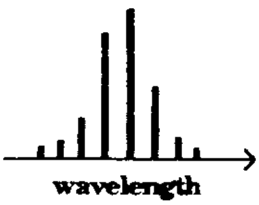


Output power:

- Total: 5 ÷ 20 mW
- Into MM fibre: 2 ÷ 3 mW
- Into SM fibre : ~ 1 mW

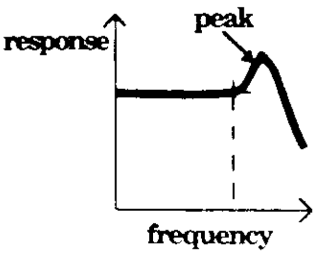
Threshold current: 10 ÷ 50 mA

Current above threshold: 30 ÷ 50 mA



Spectral width (FWHM):

- ≤ 5 nm (multi longitudinal mode)
- ≤ 0.001 nm (single longitudinal mode, broadens to some 0.1 nm under mod.)



Bandwidth:

- 1 ÷ 10 GHz
  (depending on structure and package)

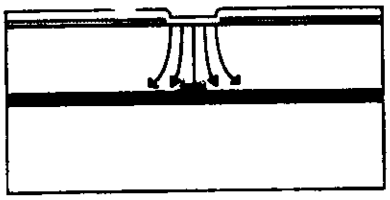
27816

LATERAL CONFINEMENT

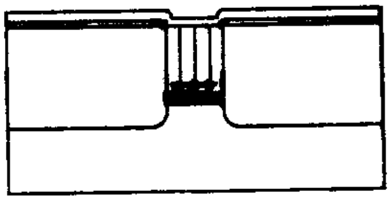
Poor confinement of the laser mode field results in:

- **P-I non-linearity**
- **unstable coupling to the fibre**
- **high relaxation oscillations**
- **noise**
- **self-pulsations**

Stable lateral confinement can be obtained by:

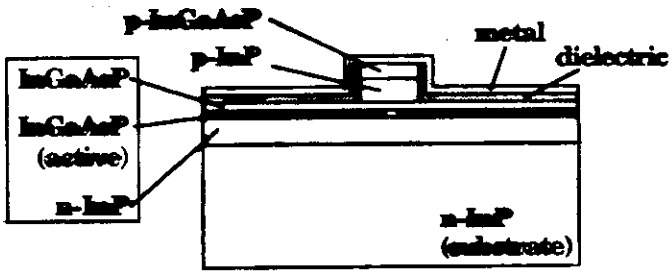


Gain guided laser diode

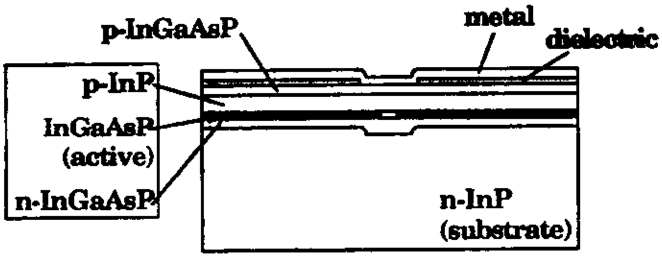


Index guided laser diode

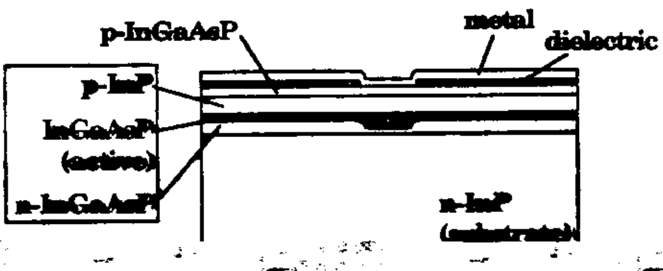
WEAKLY INDEX-GUIDED LASER STRUCTURES



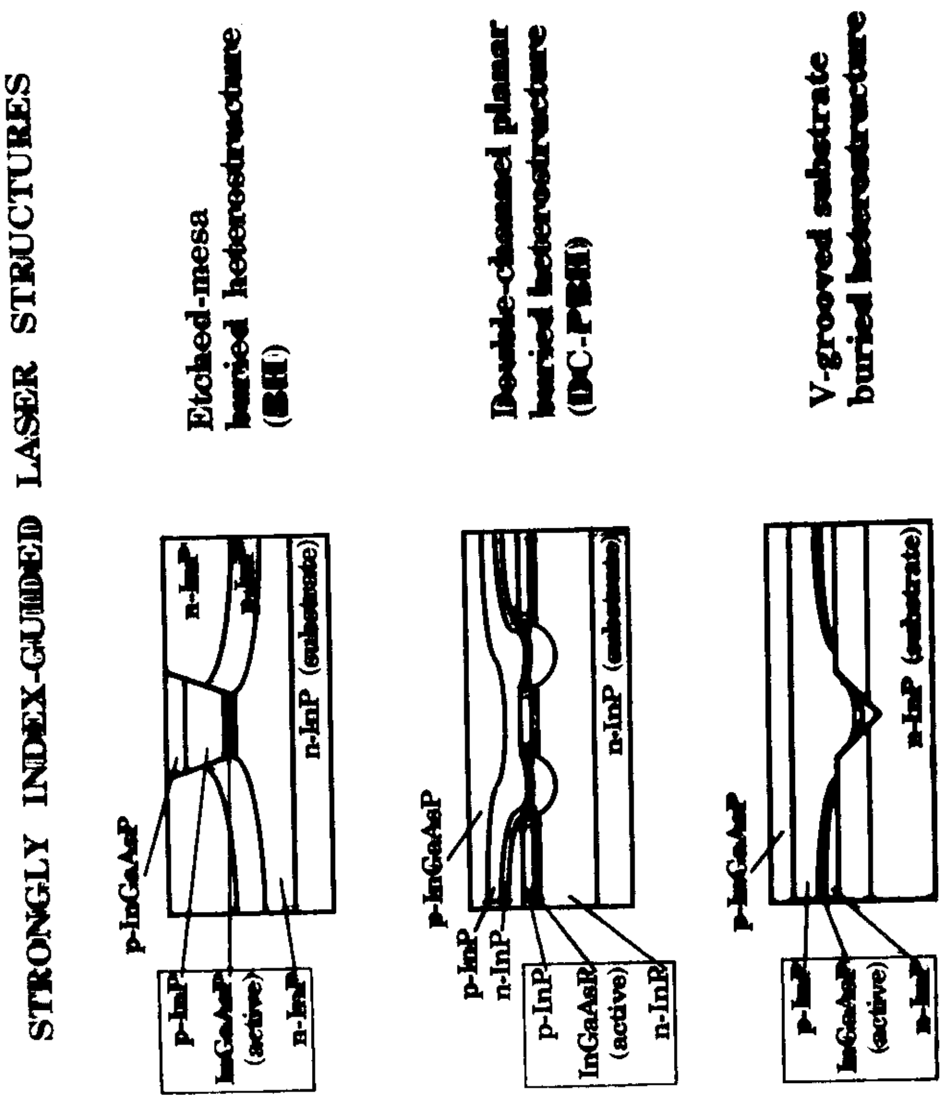
Ridge waveguide



Channeled substrate planar (CSP)

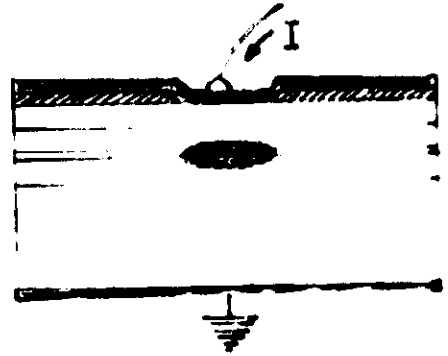


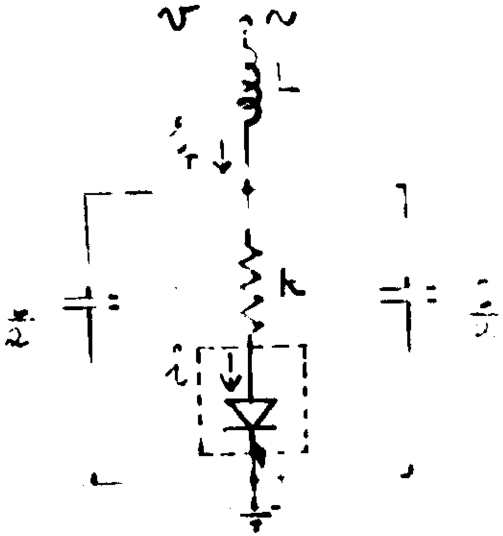
Rib waveguide



CIRCUITO EQUIVALENTE

(DIODO LASER + PARAMETRI PARASSITI)



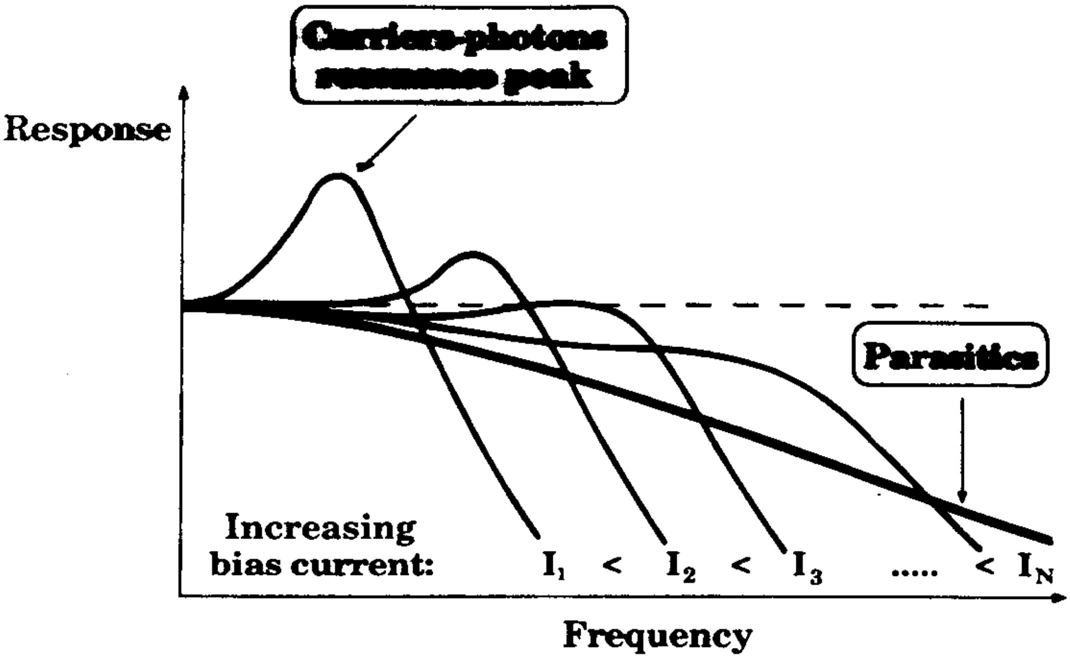


$L = 0.2 \div 2$ nH

$C = 2 \div 50$ pF

$R = 2 \div 10\ \Omega$

FREQUENCY RESPONSE OF LASER DIODE

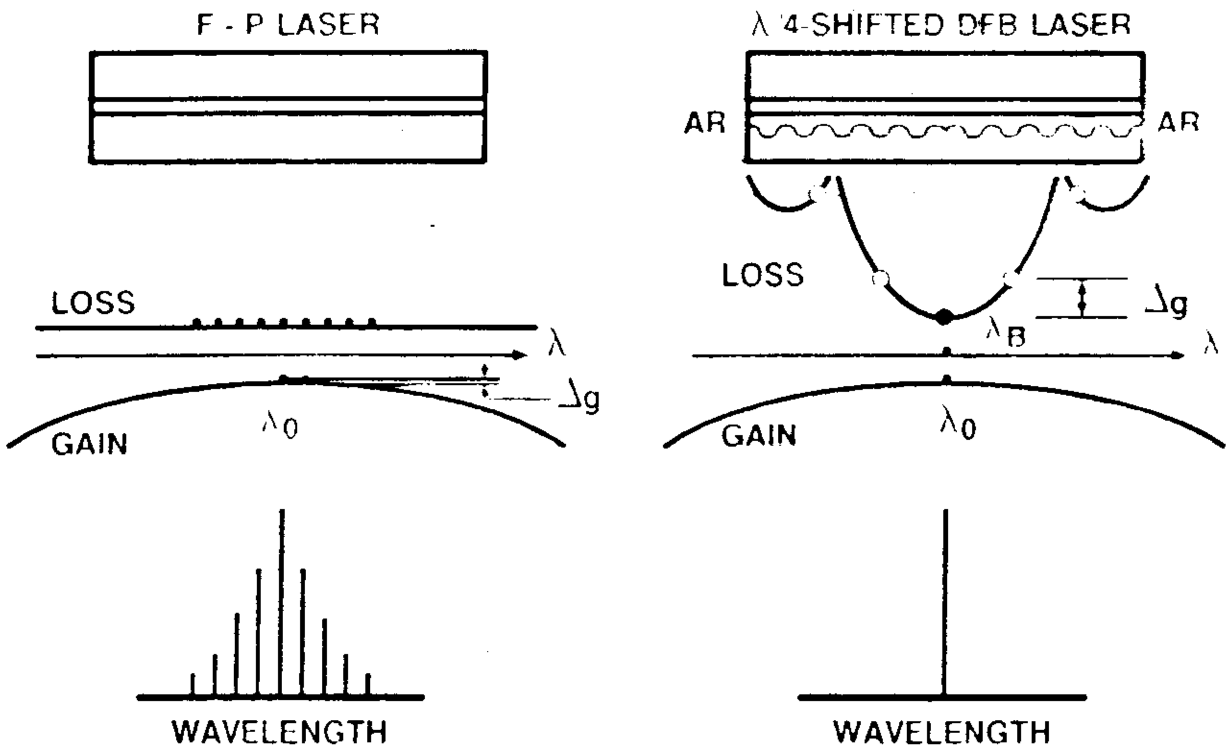


Two factors limit the laser frequency response:

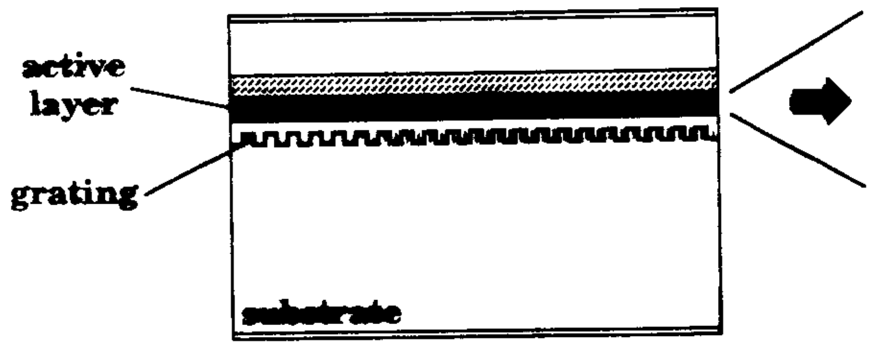
- **Carriers-photons resonance in the active region**
- **Parasitics (junction capacitance, package....)**

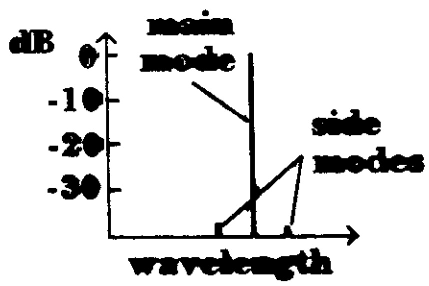
27809

Single Frequency Operation Of DFB Lasers

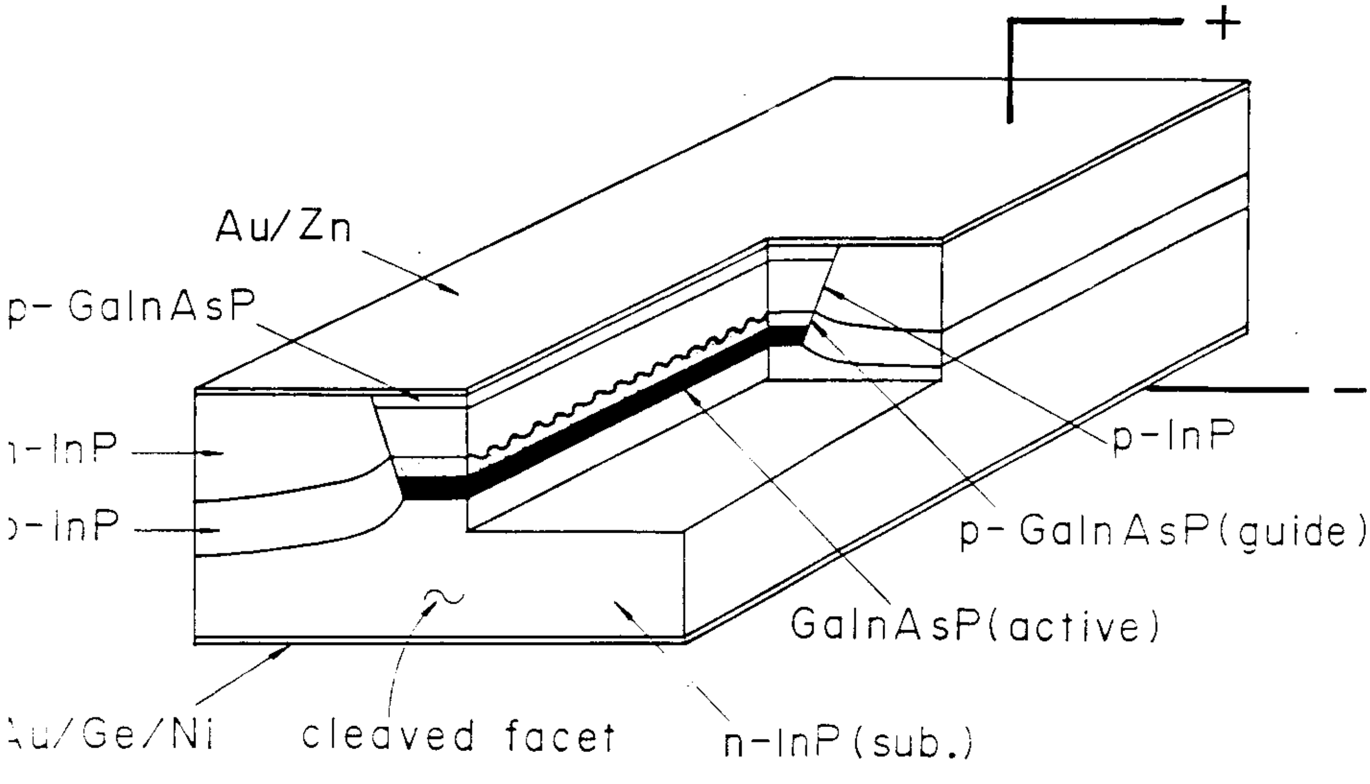


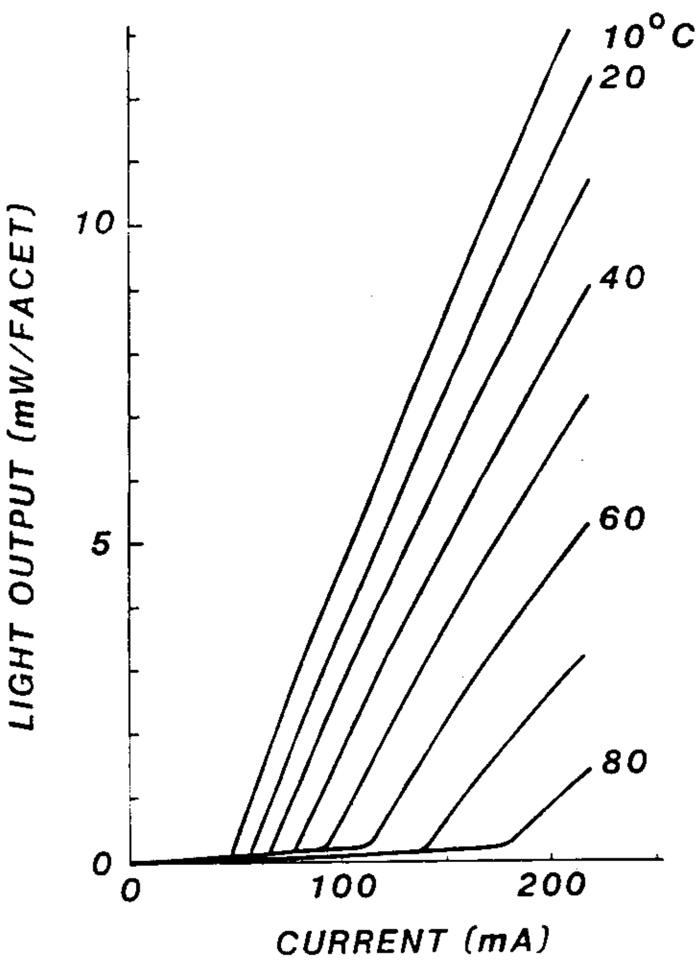
DISTRIBUTED FEEDBACK LASER DIODE

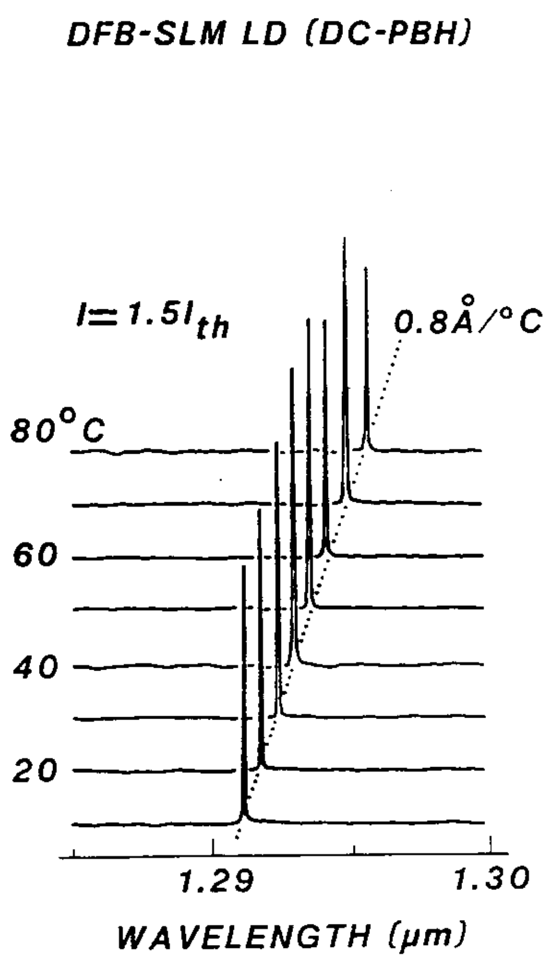




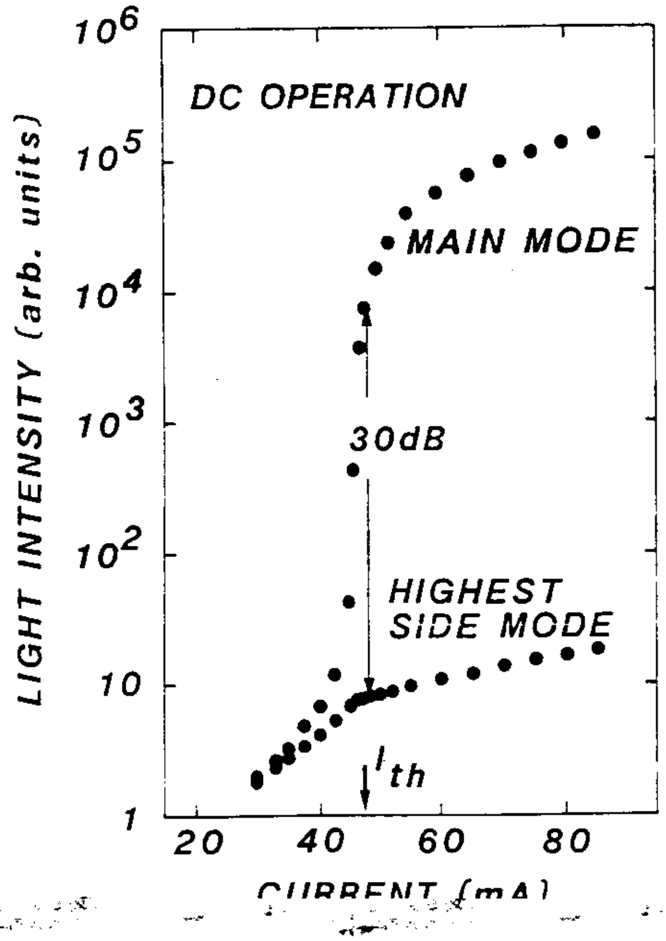
- side mode suppression ratio: > 30 dB

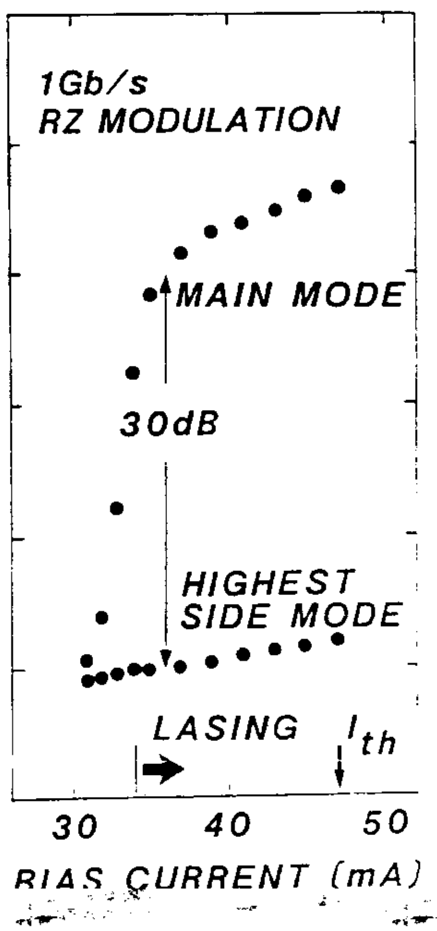




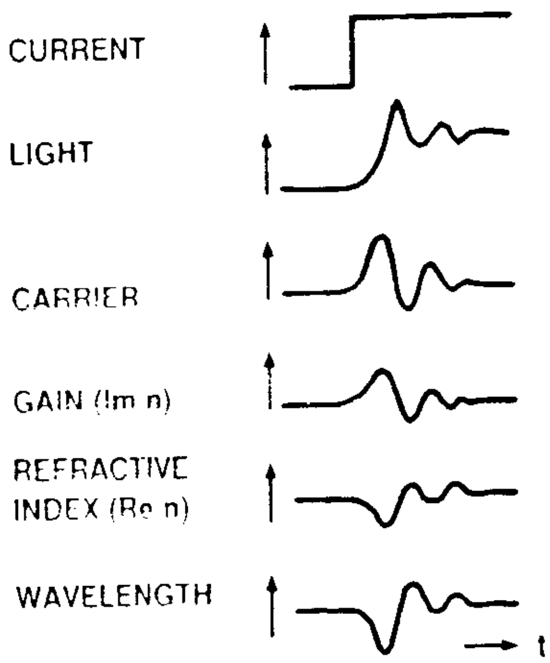


CHARACTERISTICS OF AN AR-COATED DFB LASER





Spectrum Broadening Under Modulation

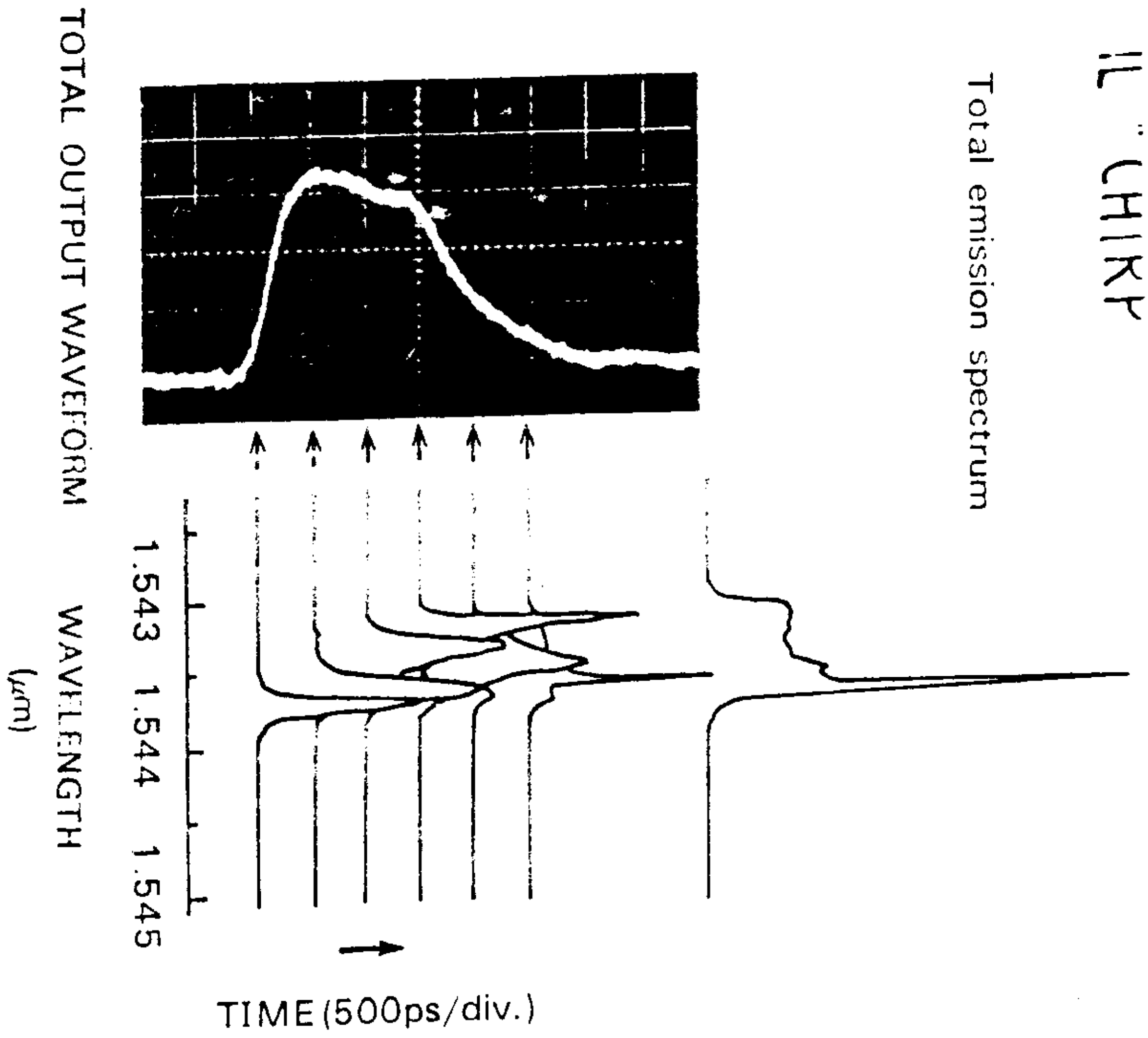


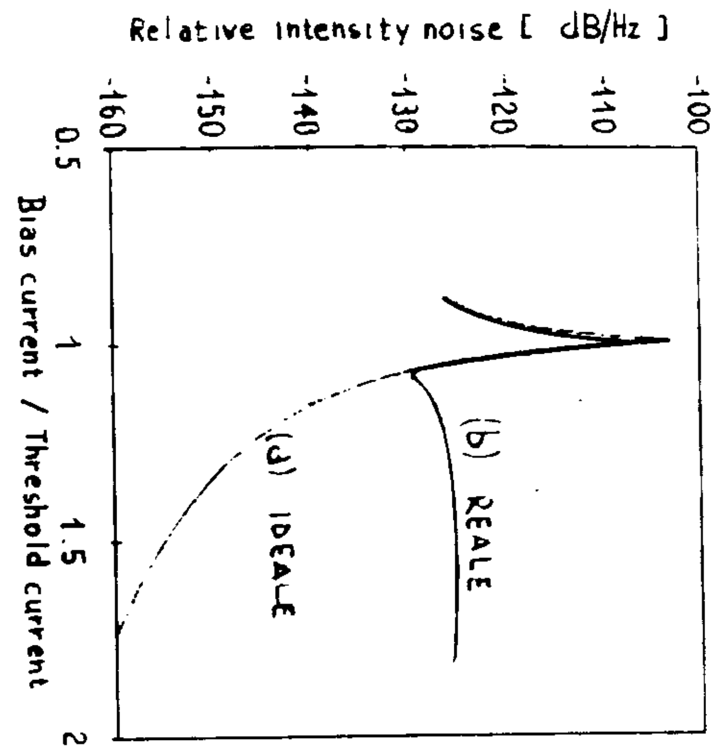
Intensity modulation

- Spectrum broadening (frequency chriping)
- Pulse distortion due to dispersion

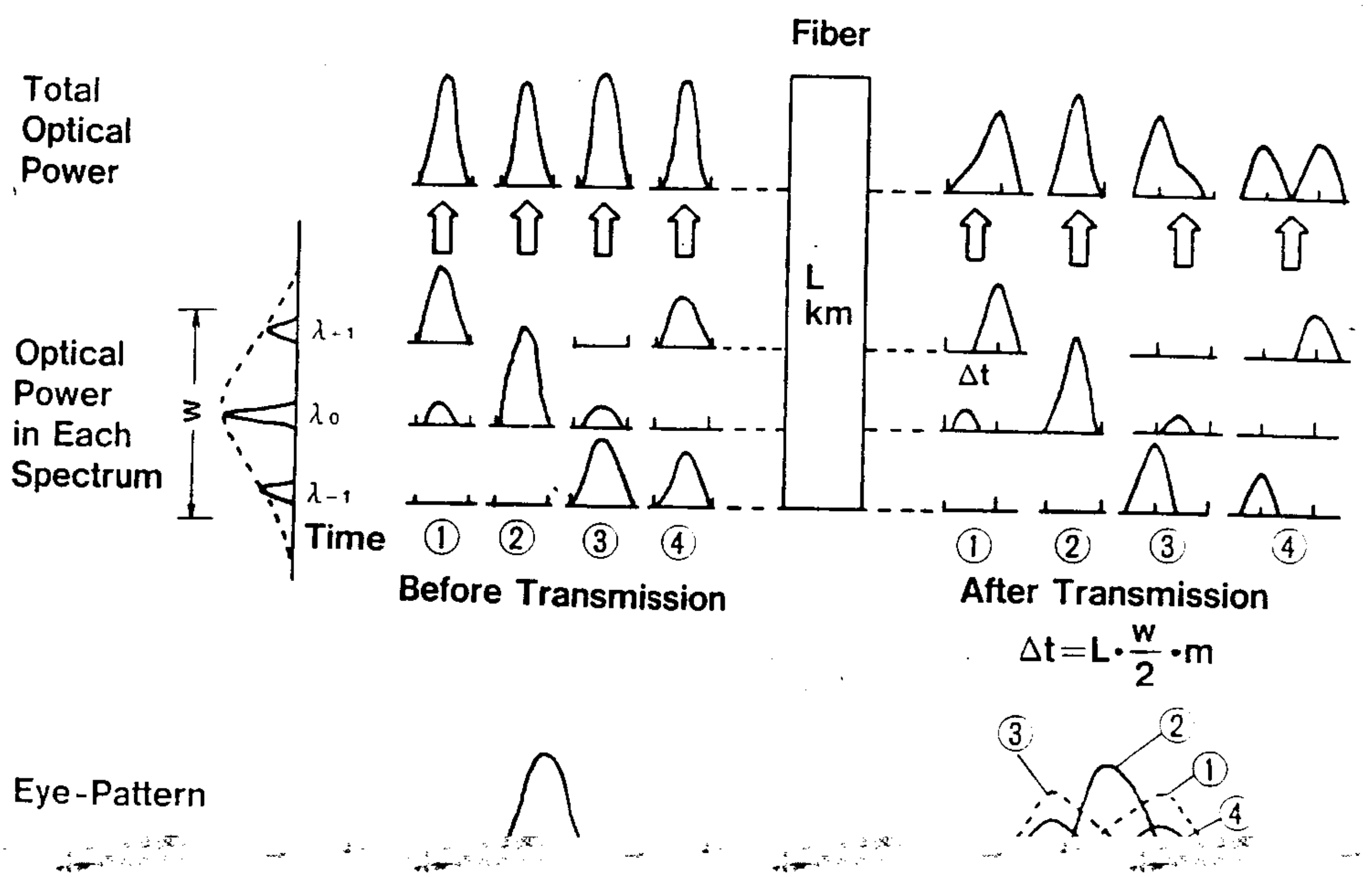
FM noise

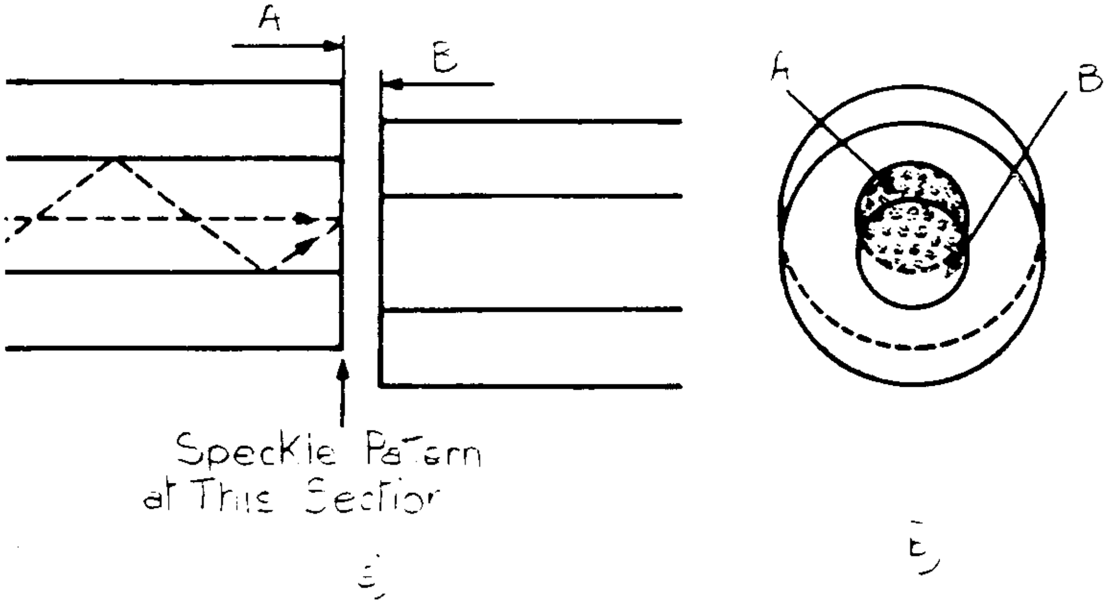
- Laser linewidth broadening



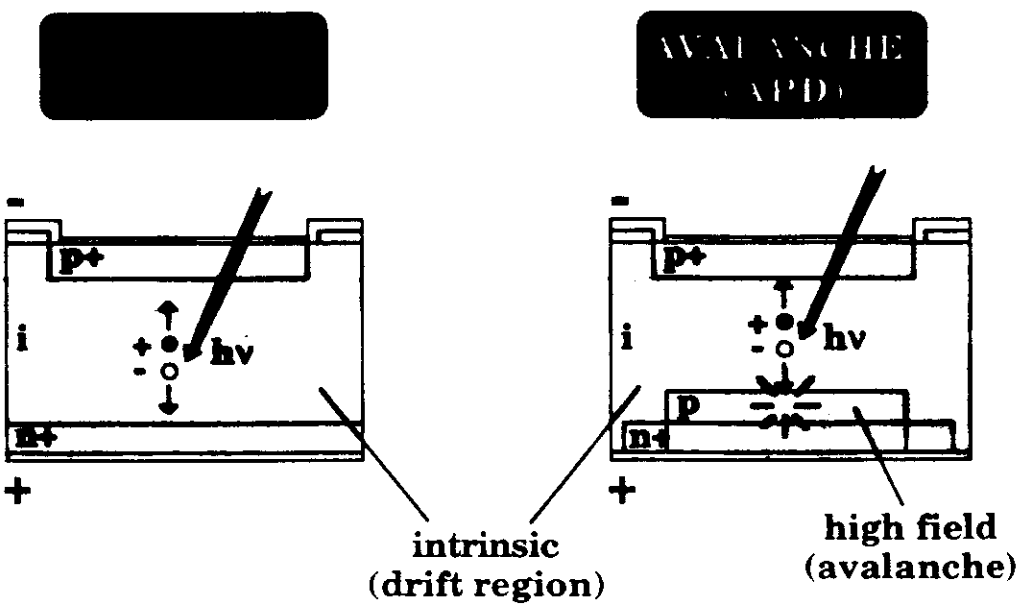


LD MODE PARTITION NOISE





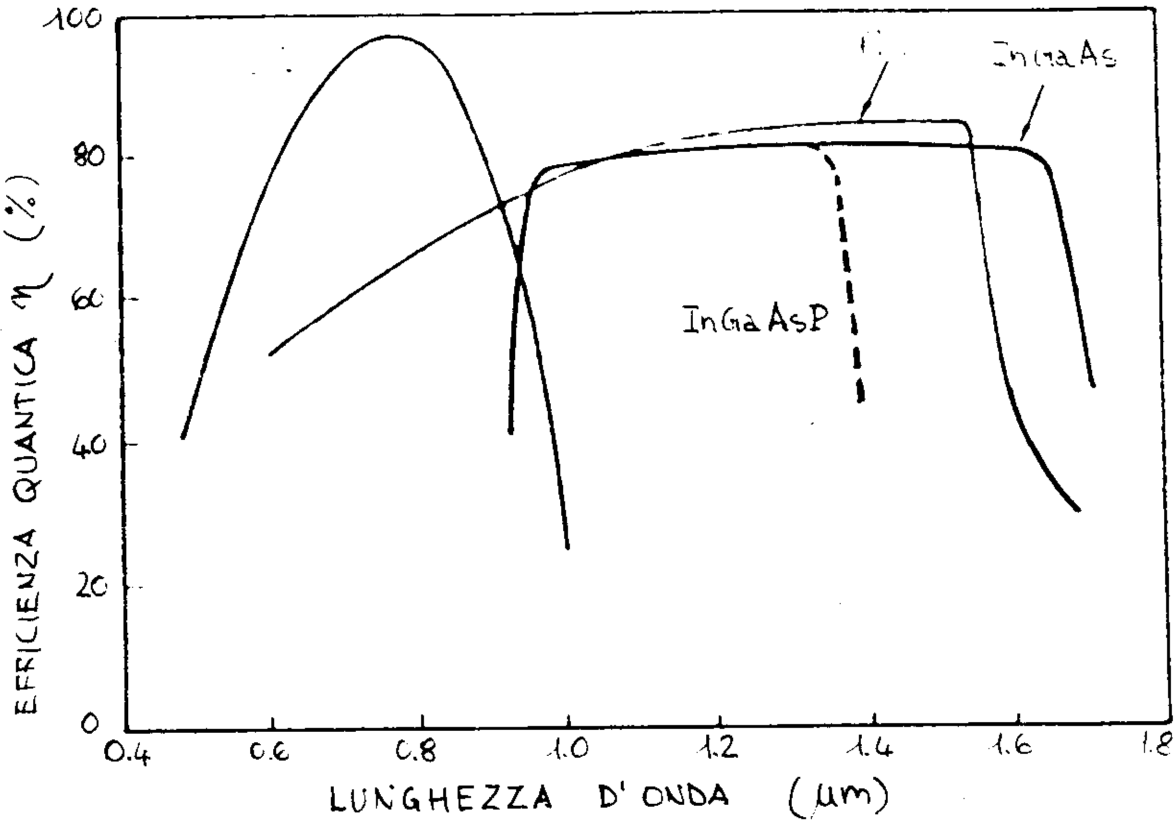
PHOTODETECTORS



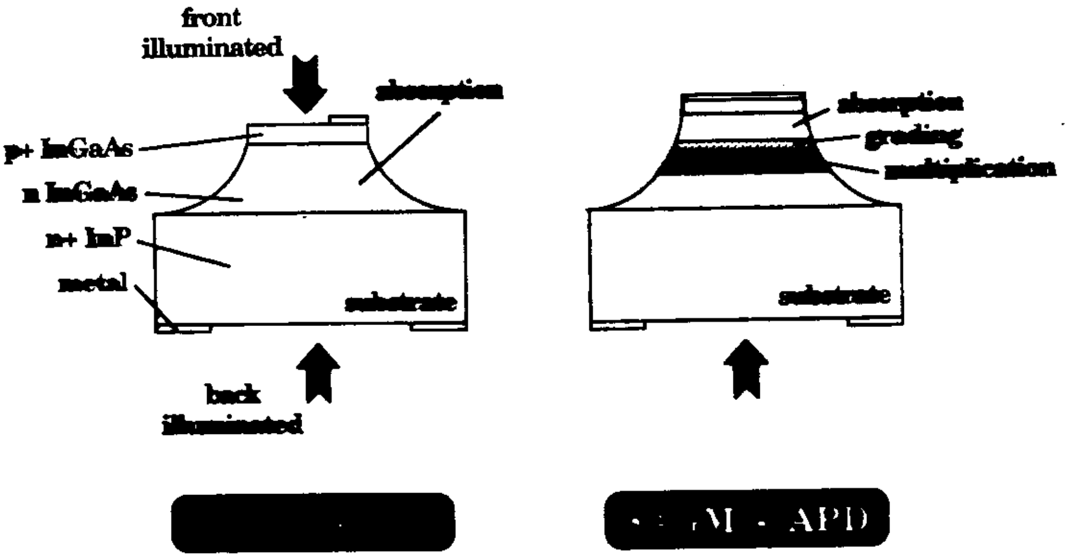
Material:

- **Silicon** up to: ~1 µm
- **Germanium** " ~1.5 µm
- **InGaAs** " ~1.6 µm

RISPOSTA

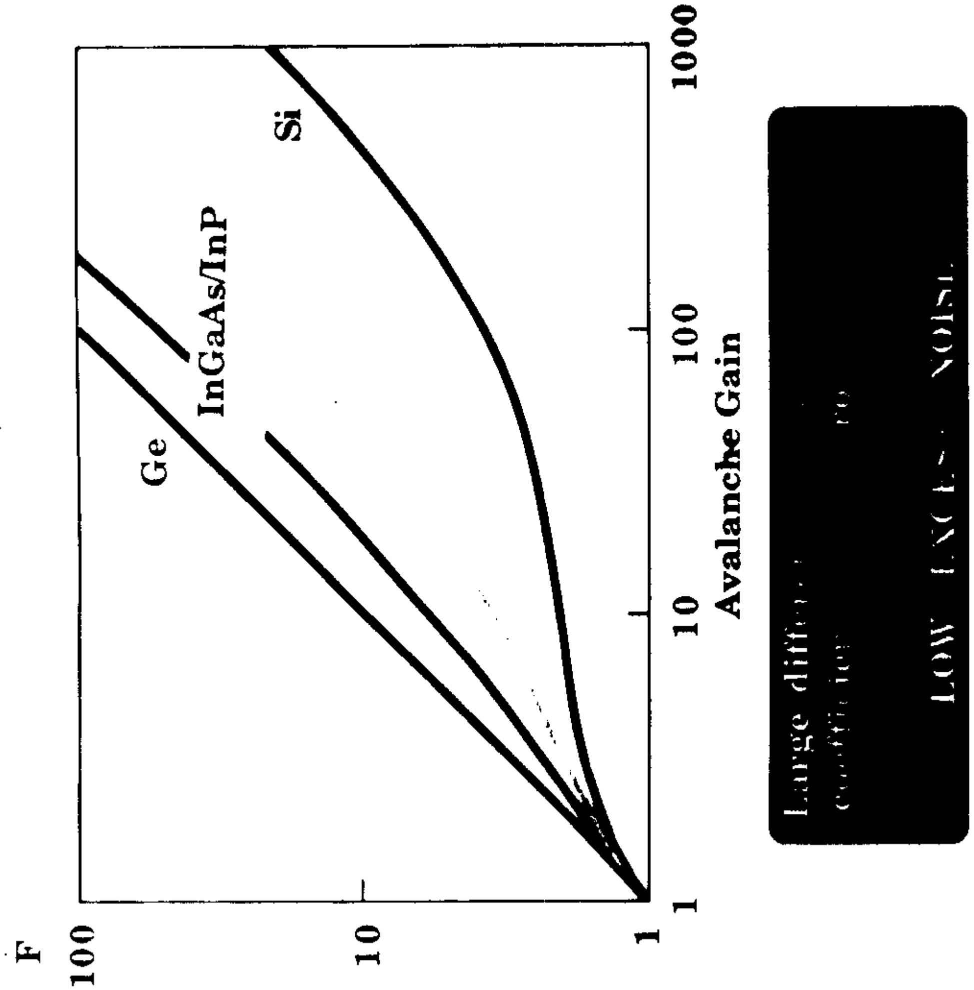


PHOTODETECTORS FOR 1.3 ÷ 1.55 μm

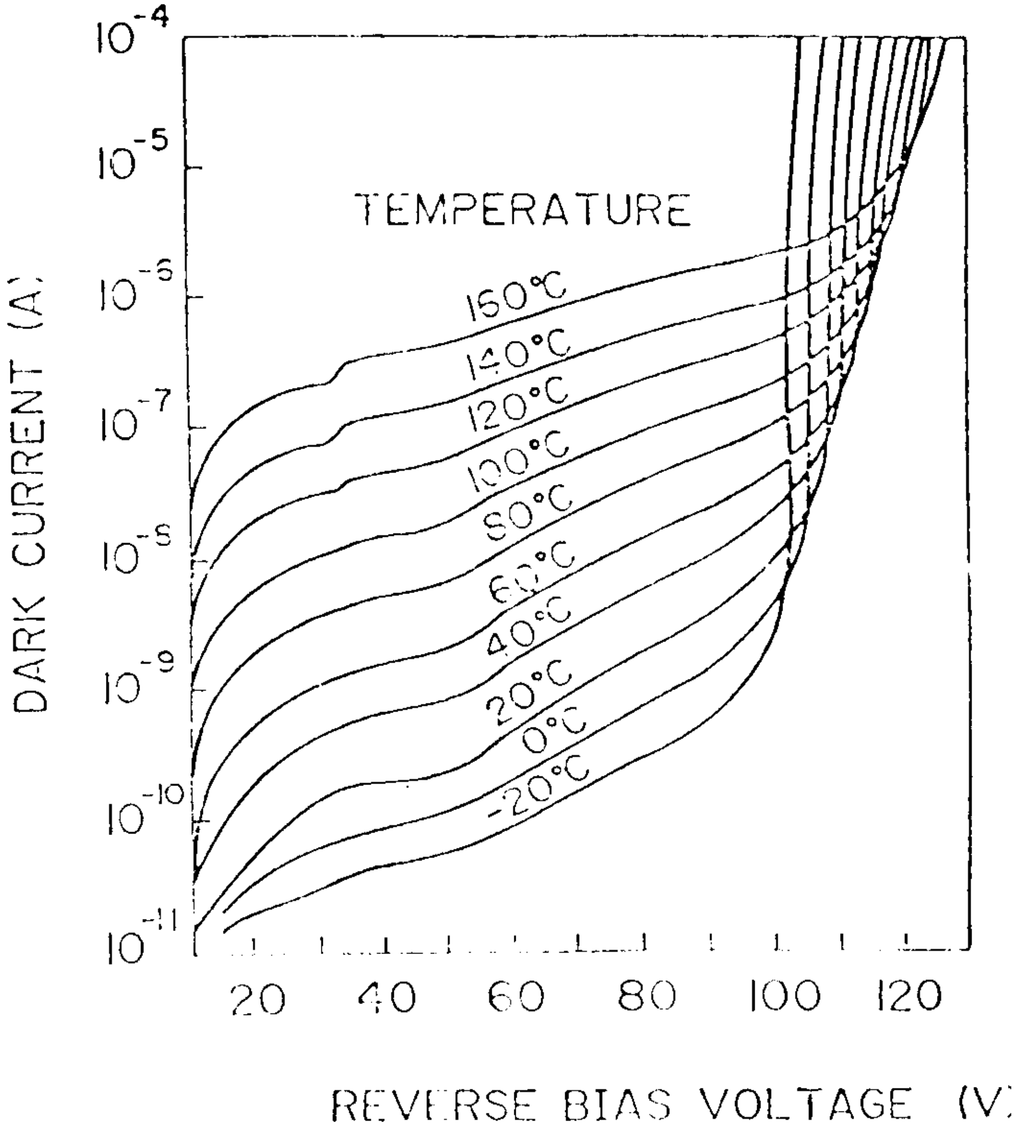


- InGaAsP/InP heterostructure
- epitaxial growth
- 30 ÷ 100 μm Ø useful area
- mesa or planar structure

27818

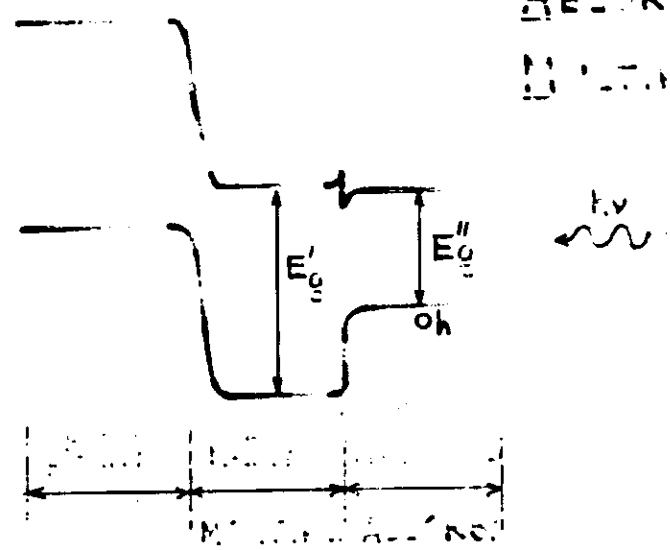


[illegible] InGaAs/InP



SAM - APD

SEPARATE
ABSORPTION
MULTIPLICATION

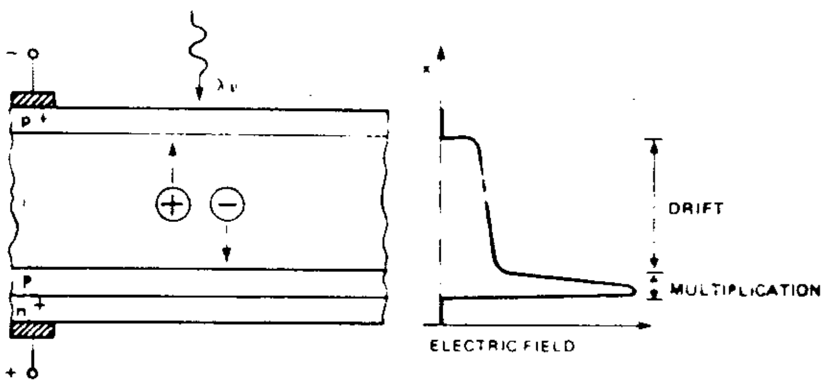


$$\langle i^2 \rangle = 2qI\,\Delta f$$

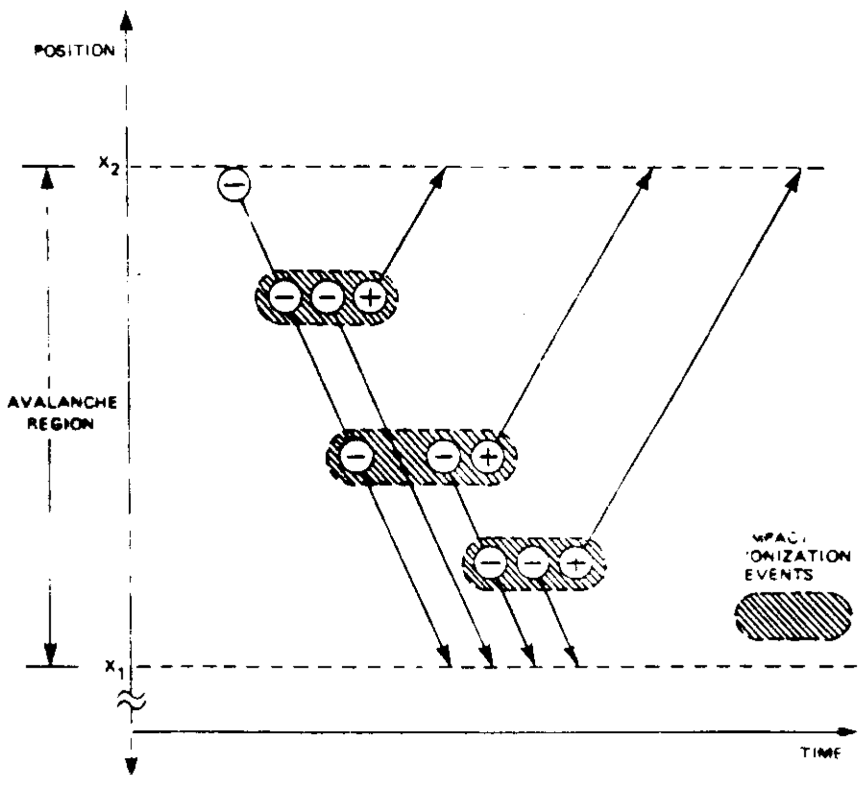
$$\langle i^2 \rangle = 2qI M^2 F(M)\,\Delta f$$

$$F(M) = KM + (1-K)(2-1/M)$$

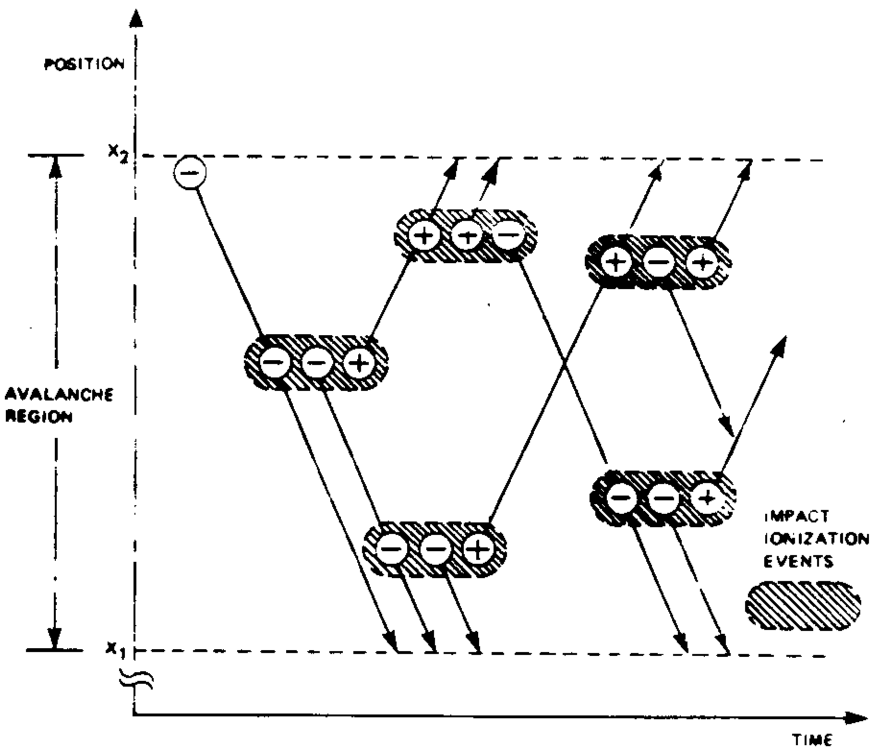
$$K = \min\left\{\frac{\alpha}{\beta}\,;\,\frac{\beta}{\alpha}\right\}$$



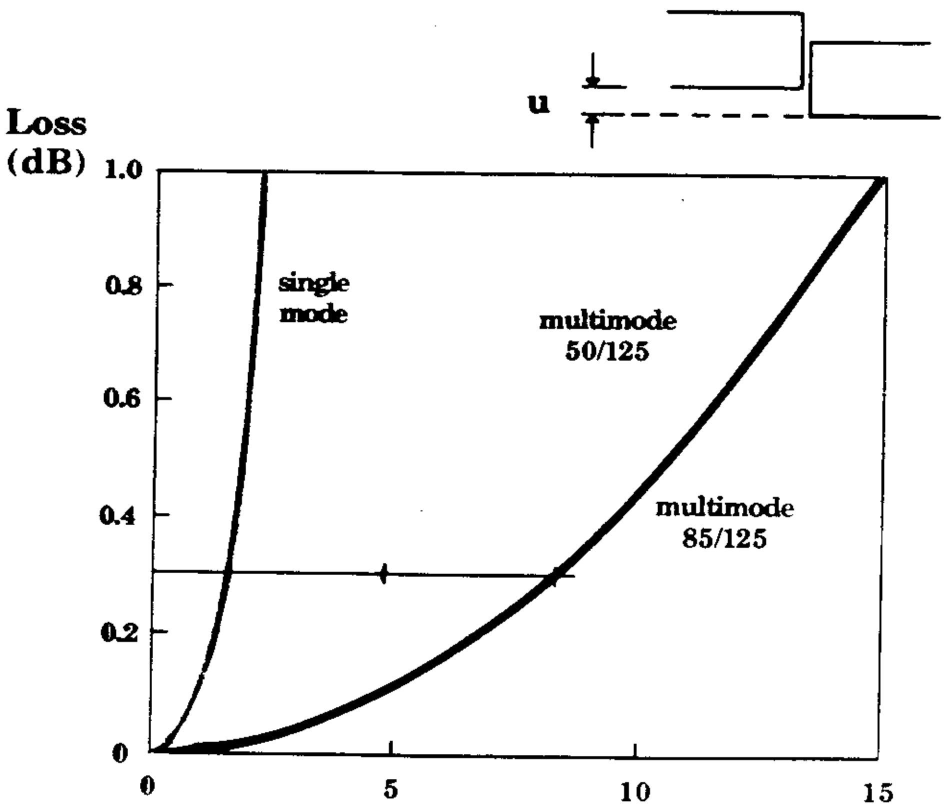
DRIFT
MULTIPLICATION
ELECTRIC FIELD



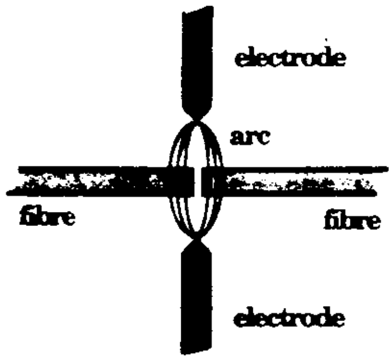
POSITION
AVALANCHE REGION
TIME
EVENTS

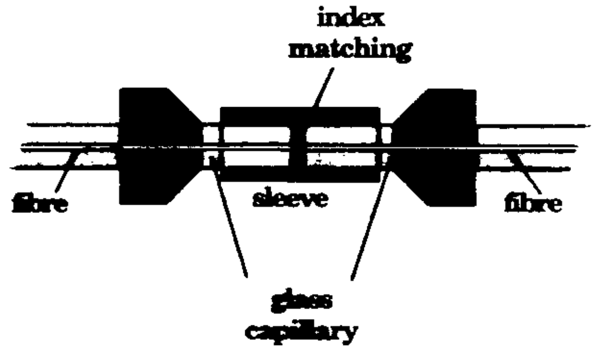


COUPLING LOSS DUE TO LATERAL MISALIGNMENT



SPLICES





FUSION

MECHANICAL

Problems:

- **Core alignment (single mode)**
- **Local operation**
- **Splice loss measurement**
- **Mechanical strength**

Typical splicing loss : < 0.1 dB

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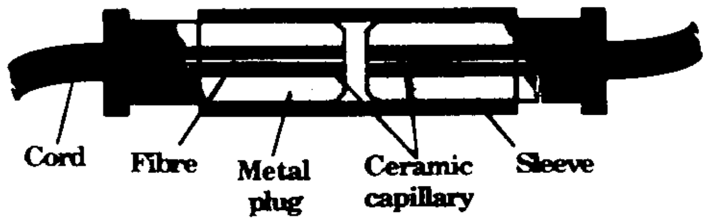
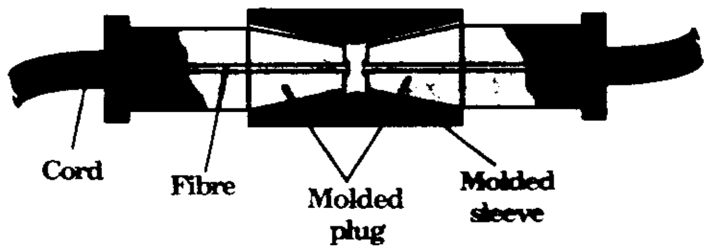
CONNECTORS



Cylindrical



Biconical

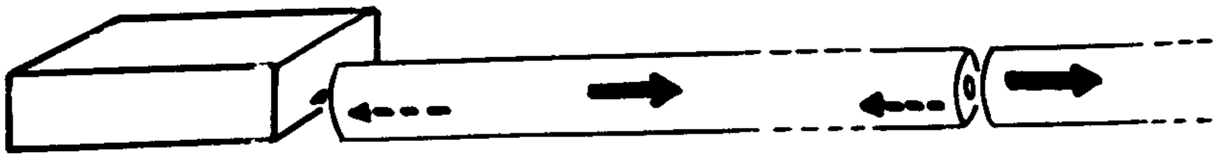
Several options:

- cylindrical, biconical, V-groove, ball and socket, ...
- metal, plastic, ceramic, glass, ...

Typical loss: < 0.5 dB

CSELT 27826

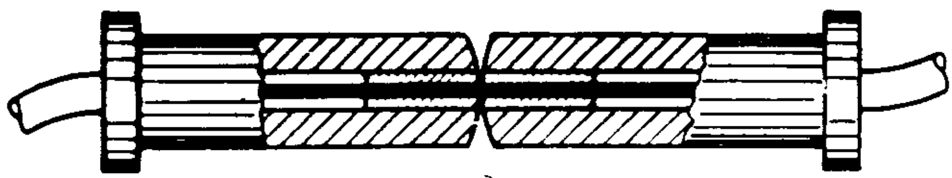
LASER DIODE PERTURBATION
DUE TO EXTERNAL REFLECTIONS



LASER + EXT. REFLECT. → NOISE
→ NON LINEARITY
→ SPECTRAL INSTABILITY

+ MISALIGN. JOINTS → [illegible]
+ CHROMATIC DISP. → JITTER.

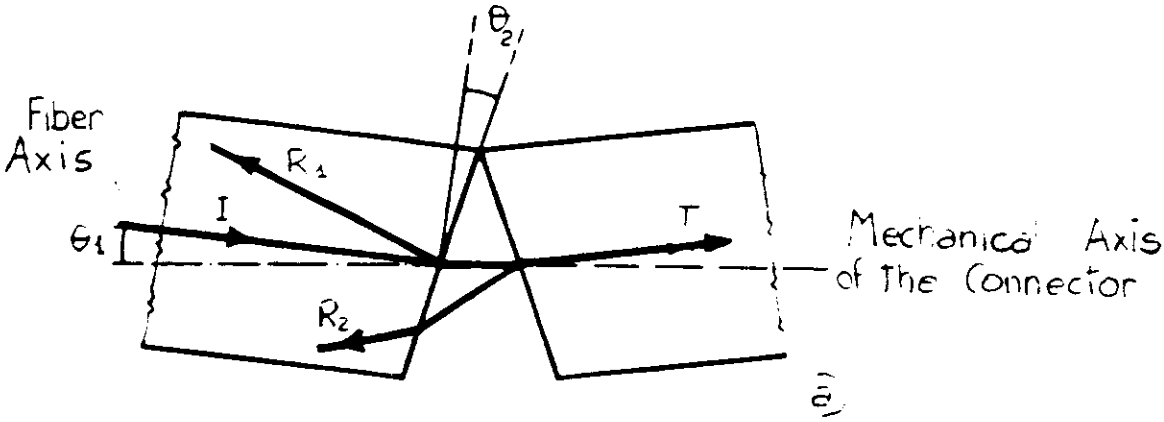
CONNECTION [illegible] A [illegible]

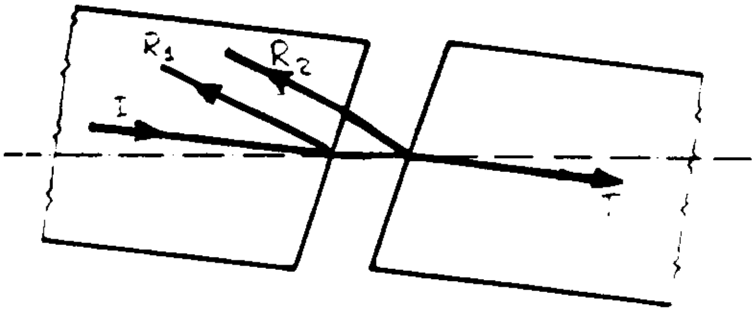


a)

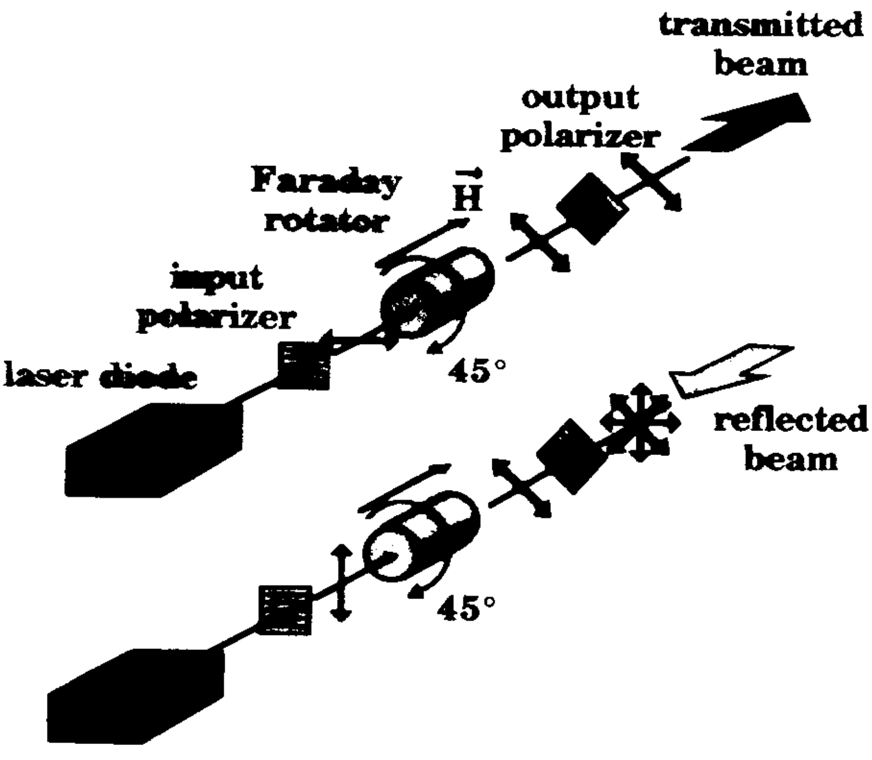
[illegible]

b)



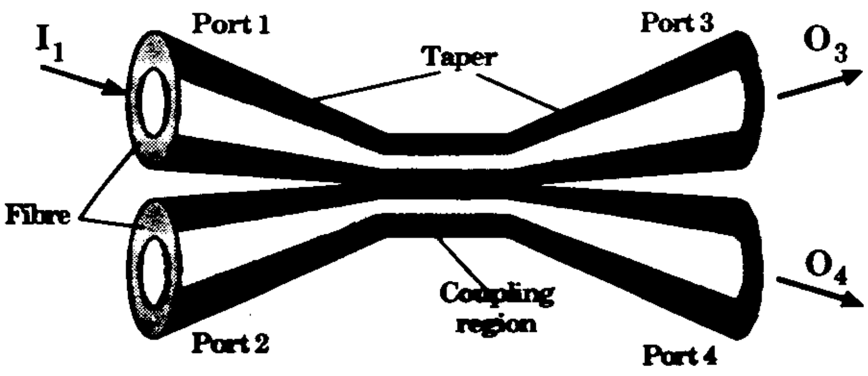


FARADAY EFFECT OPTICAL ISOLATOR

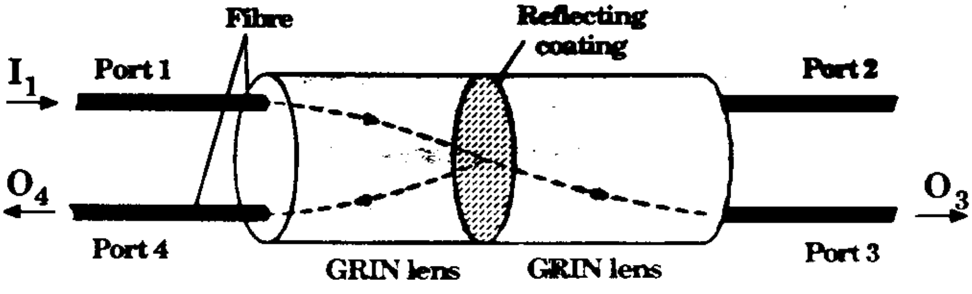


- typical isolation: 25 ÷ 30 dB
- typical insertion loss: 1 ÷ 1.5 dB

DIRECTIONAL COUPLERS



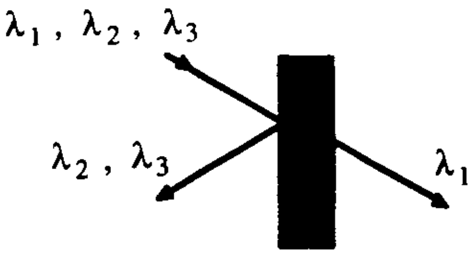
Fused fiber coupler

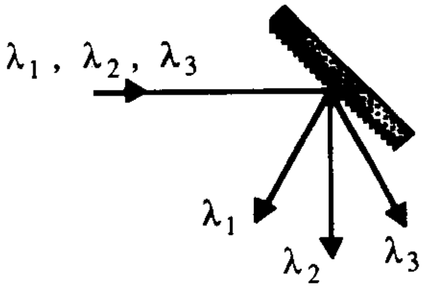


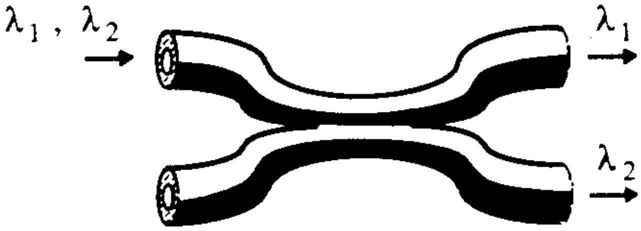
Microoptic coupler

27812

WAVELENGTH DIVISION MULTIPLEXING







single mode coupler

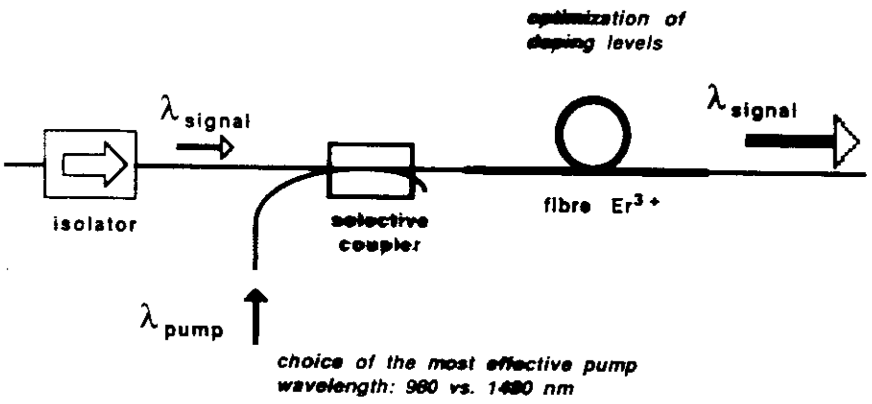
27814

OPTICAL AMPLIFIERS

- **ACTIVE FIBRE AMPLIFIERS:** SINGLE MODE FIBRES, DOPED WITH ERBIUM (FOR 1550 nm) OR WITH NEODIMIUM (FOR 1300 nm) OPTICALLY PUMPED

- **SEMICONDUCTOR AMPLIFIERS:** LASER DIODE STRUCTURES, MODIFIED TO AVOID FEEDBACK, ELECTRICALLY PUMPED

ACTIVE FIBRE AMPL FIERS. PRESE[illegible]SSUES



CHOICE OF THE PUMP WAVELENGTH:

	980 nm	1480 nm
fficiency:	*optimum*	*good*
ump laser:	*InGaAs/AlGaAs/InP diode*	*InGaAsP/InP diode*
elective coupler	*easy*	*critical*
emote pumping:	*difficult*	*efficient*

BEST PERFORMANCE OF OPTICAL AMPLIFIERS

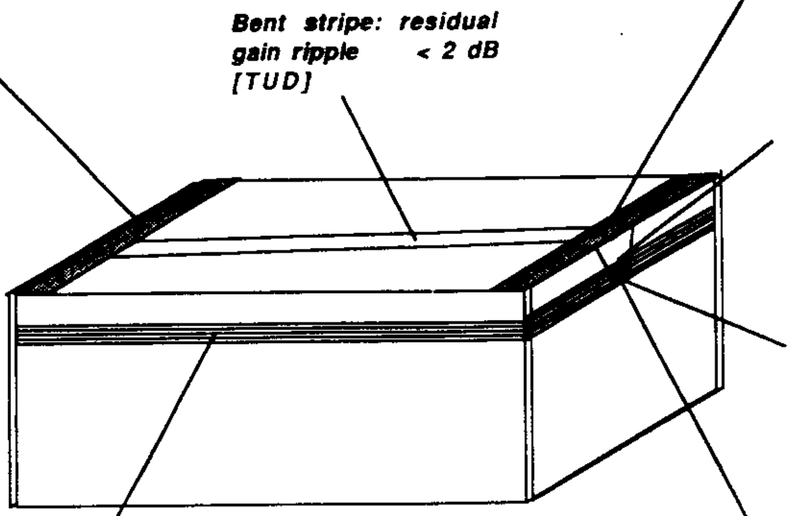
		LASER DIODE	Er^{3+} FIBRE
Internal gain (dB)		30	30-34
Fibre-to-fibre gain (dB)		22	30-34
Residual ripple (dB)		1.5	0
TE/TM gain difference (dB)		1.5	0
Bandwidth (nm)		30	30
Saturation power (dBm)		16	14
Noise figure (dB)		6	5
Opt.pump efficiency (dB/mW)	@ 528 nm	n.a.	0.3
	@ 980 nm	n.a.	3.9
	@ 1480 nm	n.a.	1.0
Intermodulation		high	low

SEMICONDUCTOR OPTICAL AMPLIFIERS: RECENT IMPROVEMENTS

Multilayer anti-reflection coating: R < 0.0003 over 320 nm [BTRL]

Anti-reflection "windows": R < 0.0003, residual gain ripple < 1.5 dB [NEC]

***Bent stripe:** residual gain ripple < 2 dB [TUD]*



Multi-Quantum-Well structure: high saturation power,

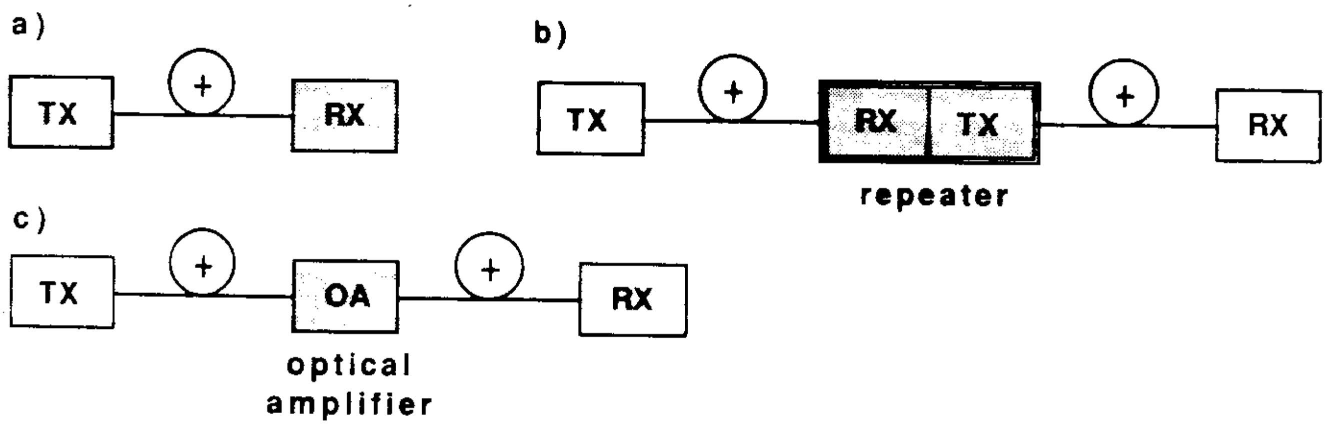
Symmetrical waveguide structure: TE - TM gain difference < 1 dB

ADVANTAGES OF OPTICAL AMPLIFICATION

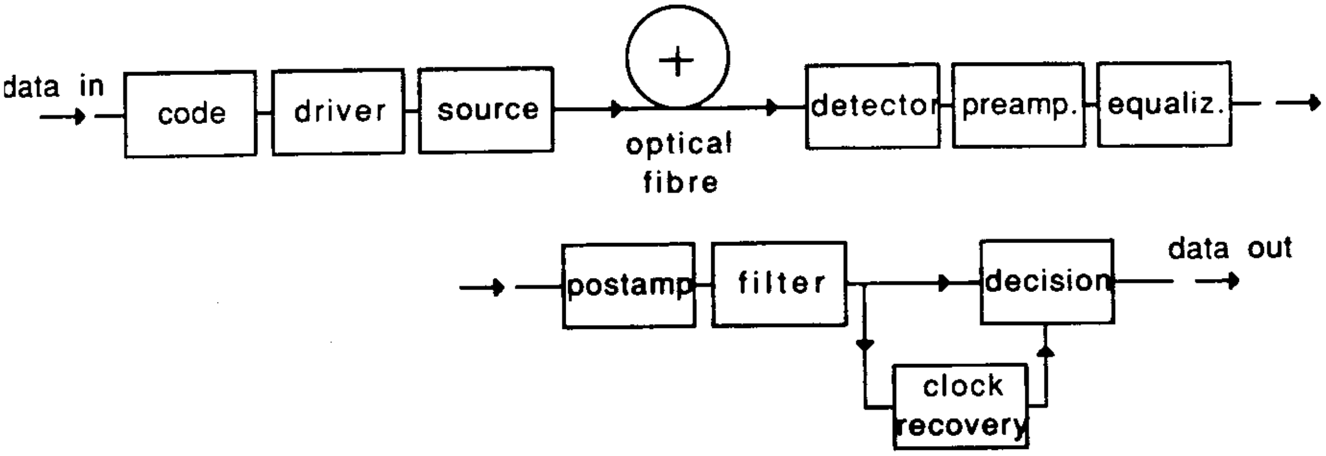
1. BIT-RATE TRANSPARENCY (bandwidth = 4÷5 THz)
2. HIGH GAIN
3. LACK OF ELECTRONIC CIRCUITS (only d.c. laser bias)
4. SMALL SIZE AND LOW POWER CONSUMPTION
5. SIMPLE AND CONSOLIDATED TECHNOLOGIES (laser diode, single mode fibre)

TELECOMMUNICATION L[illegible]WAVE SYSTE[illegible]

- TRANSMISSION OF DIGITAL INFORMATION OVER L > 1 km
- BINARY INTENSITY MODULATION
- DIRECT DETECTION —— NOW
- OPTICAL AMPLIFICATION —— EVOLUTION
- COHERENT MODULATION, HETERODYNE DETECTION —— EVOLUTION



BLOCK CONFIGURATION OF AN OPTICAL LINK



- MEASURE OF SYSTEM PERFORMANCE: **BIT ERROR RATE (B.E.R.)**
  (i.e. probability that an error is made while detecting a bit)
- RECEIVER SENSITIVITY: **MINIMUM RECEIVED OPTICAL POWER RESULTING IN ACCEPTABLE B.E.R. (typ.: 10^{-9})**

MAIN LIMITING FACTORS IN AN OPTICAL LINK

FIBRE:
- Attenuation
- Chromatic dispersion
- Modal dispersion (MM)

SOURCE:
- Power coupled into fibre
- Spectral width
- Bandwidth
- Chirp
- Partition noise
- Intensity noise
- Speckle generation

CONNECTORS:
- Insertion loss
- Modal noise

WDM DEVICES:
- Insertion loss
- Crosstalk

DETECTOR:
- Efficiency
- Bandwidth
- Noise

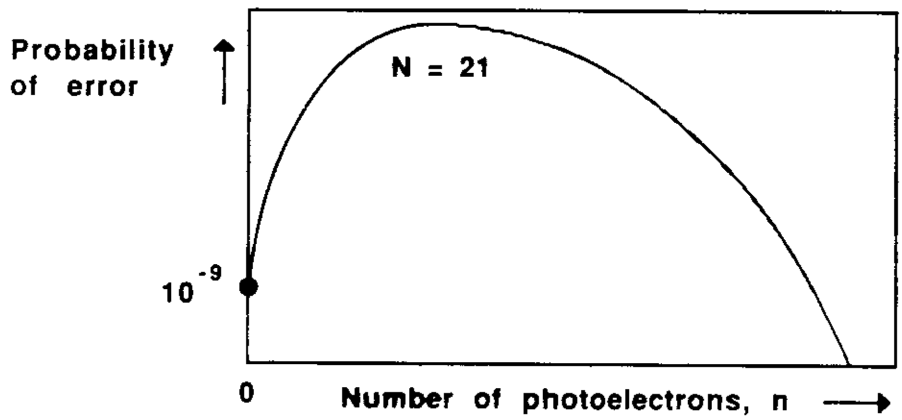
PREAMPLIFIER:
- Noise
- Dynamic range

QUANTUM LIMIT TO RECEIVER SENSITIVITY

THE PROBABILITY OF DETECTING n PHOTONS IN A TIME INTERVAL OBEYS THE POISSON DISTRIBUTION:

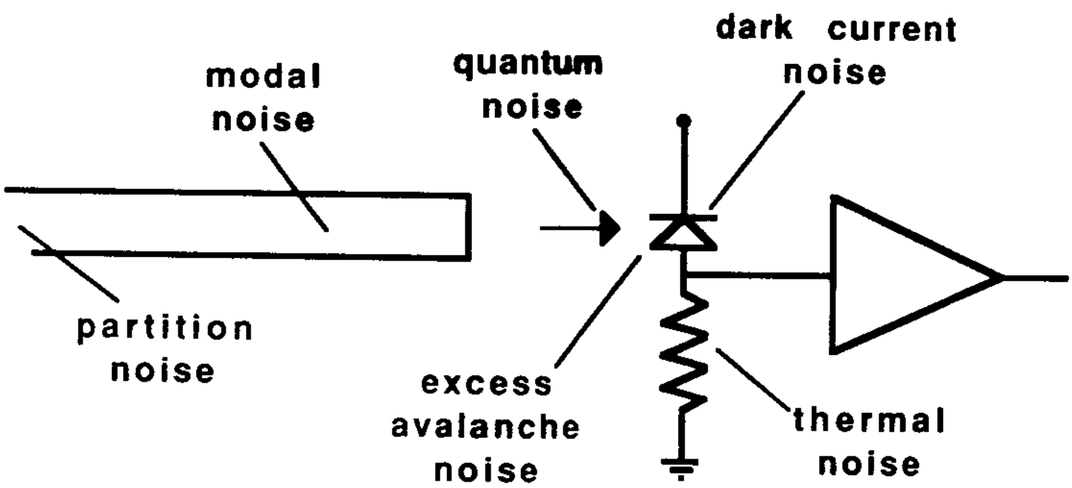
$$P(n) = \frac{\bar{N}^n}{n!} e^{-N} \quad (N = \text{average nr. of photons} = \text{variance})$$

UNDER IDEAL CONDITIONS, AN ERROR IS ONLY MADE WHEN A LIGHT PULSE IS PRESENT AND NO PHOTOELECTRONS ARE GENERATED



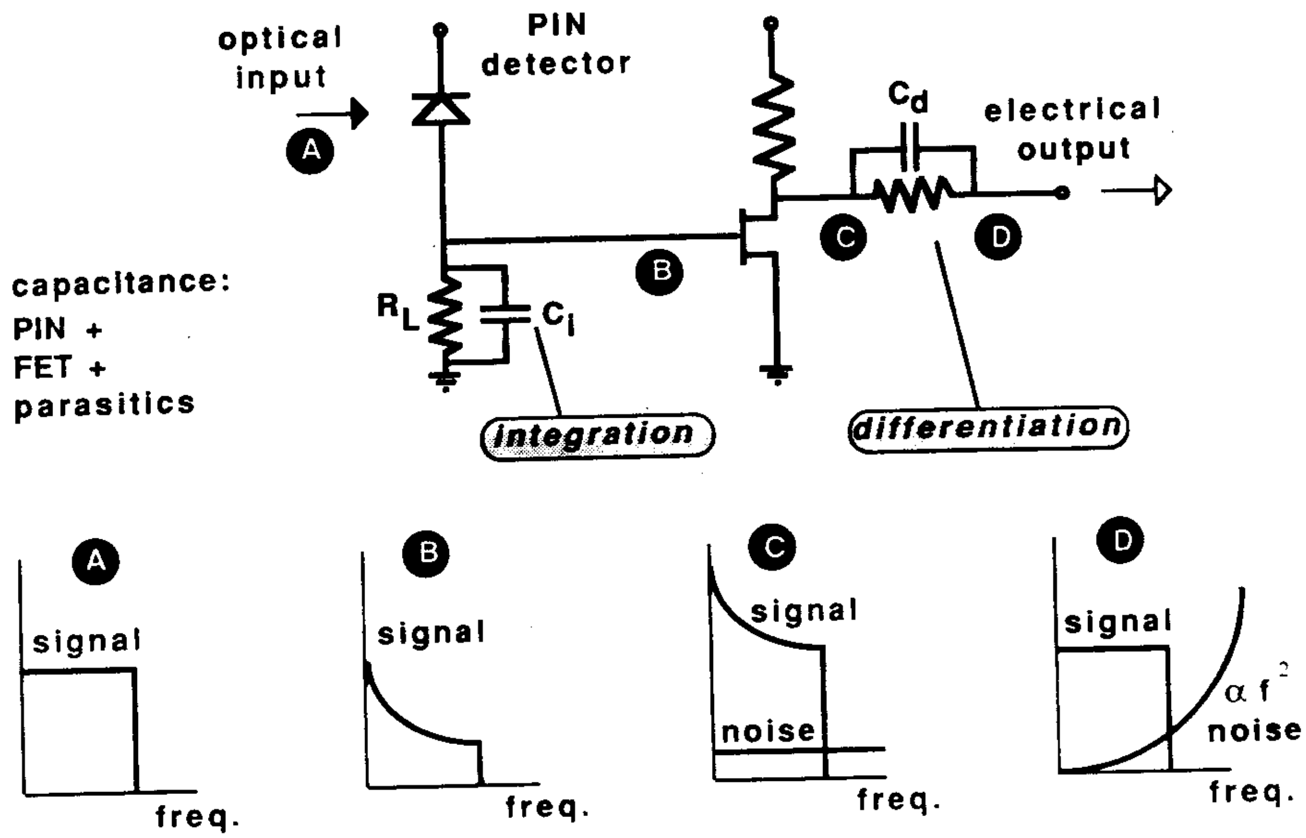
THE PROBABILITY OF ERROR (I.E. OF MEASURING n=0 IN PRESENCE OF A PULSE) REACHES 10^{-9} WHEN THE RECEIVED PULSE SHOULD GENERATE, ON AVERAGE, 21 PHOTOELECTRONS

NOISE SOURCES AT THE OPTICAL RECEIVER

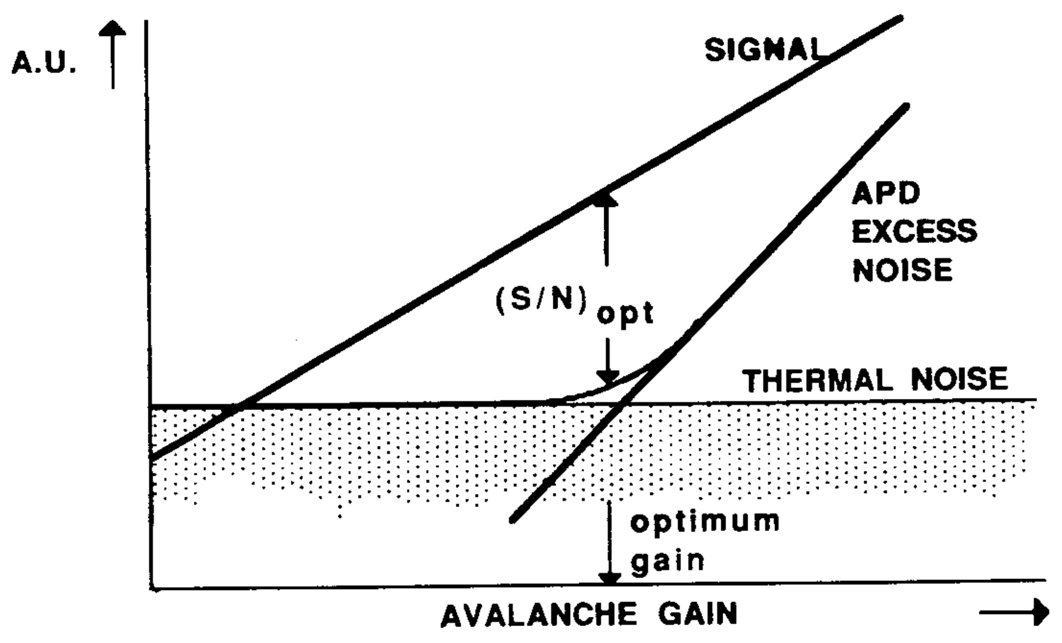


- NOISE SOURCES OTHER THAN QUANTUM NOISE REDUCE THE SYSTEM SENSITIVITY WITH RESPECT TO THE QUANTUM LIMIT (much more than 21 photons are actually necessary to detect a bit with BER $= 10^{-9}$)

PIN FET RECEIVER



APD RECEIVER

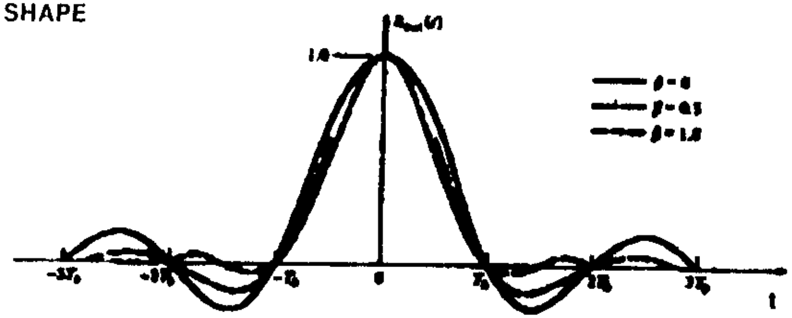


Typical improvement over PIN:

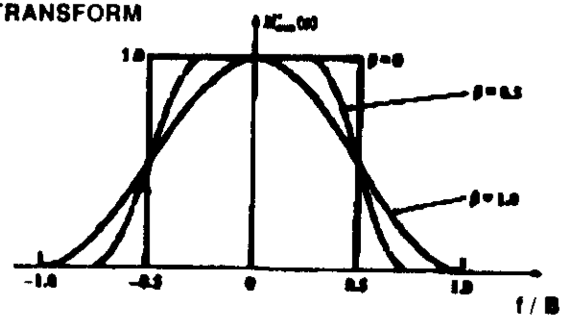
- Si APD: 14÷17 dB
- Ge APD: 5÷8 dB
- InGaAs APD: 7÷10 dB

RAISED COSINE PULSE

a) SHAPE

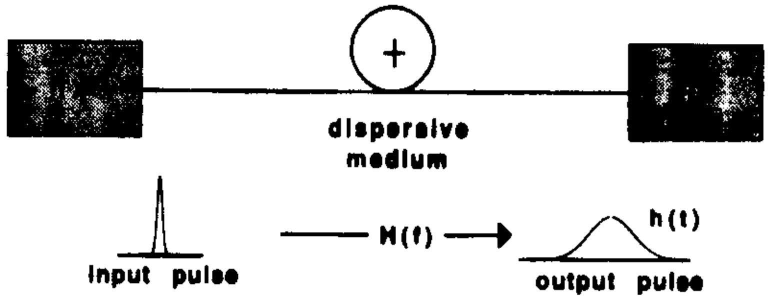


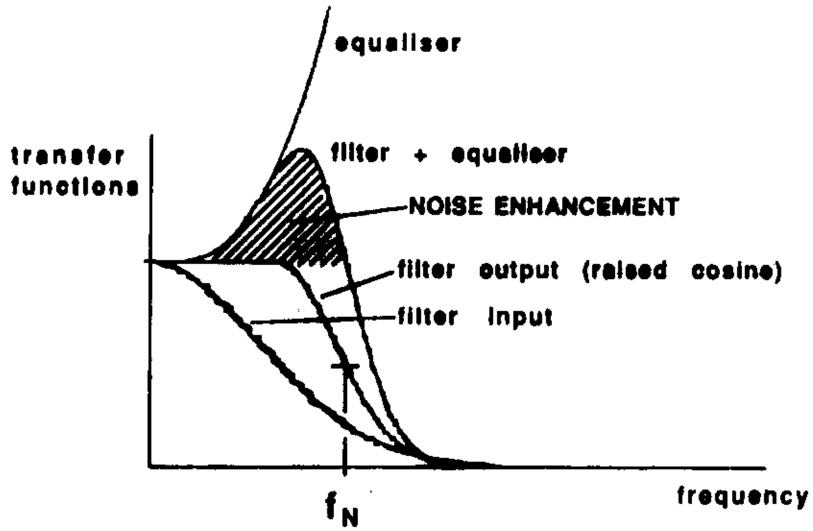
b) FOURIER TRANSFORM



- Raised cosine pulses avoid intersymbol interference

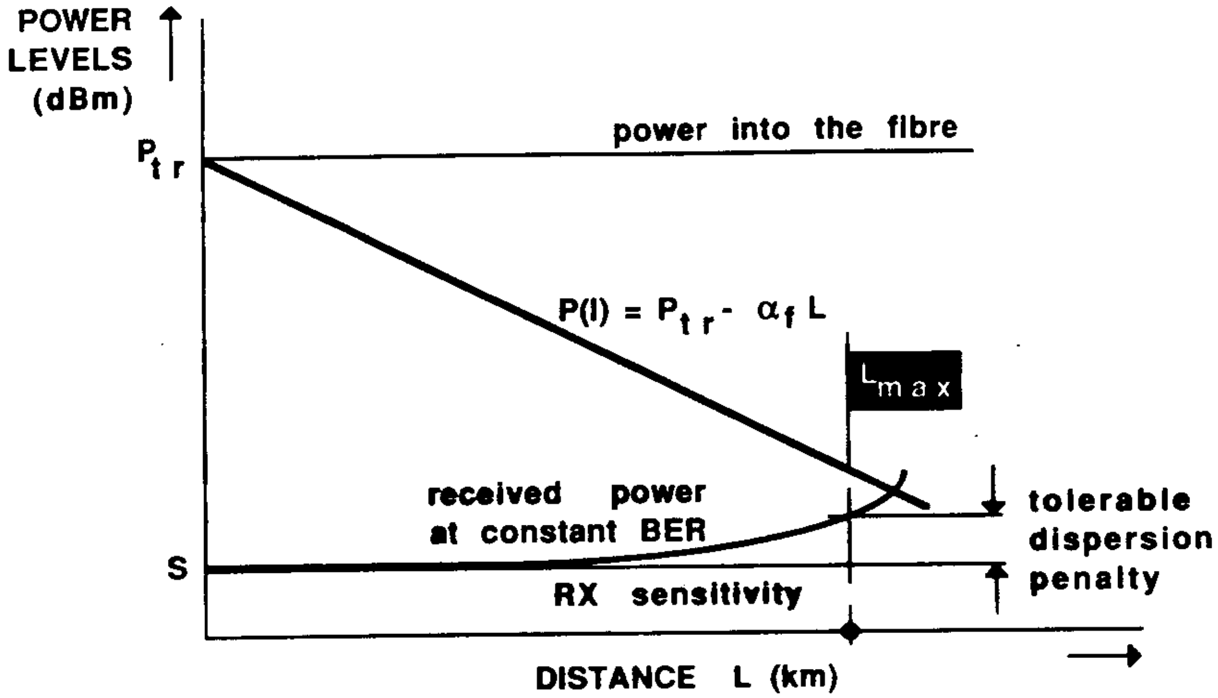
CORRECTION OF THE FIBRE DISPERSION BY THE FILTER EQUALIZER



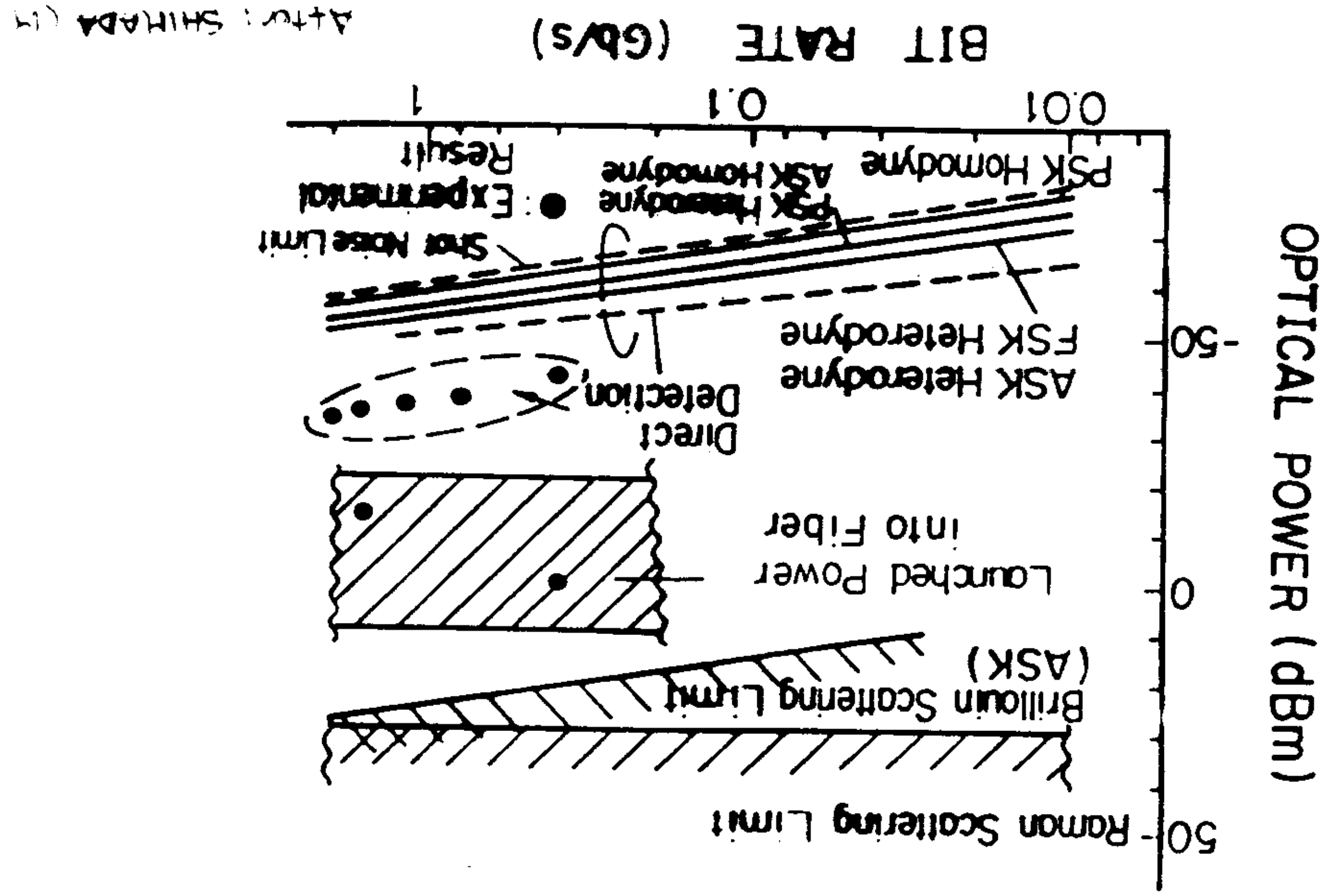


- The equaliser boosts the attenuated high-frequency components, but unavoidably increases noise

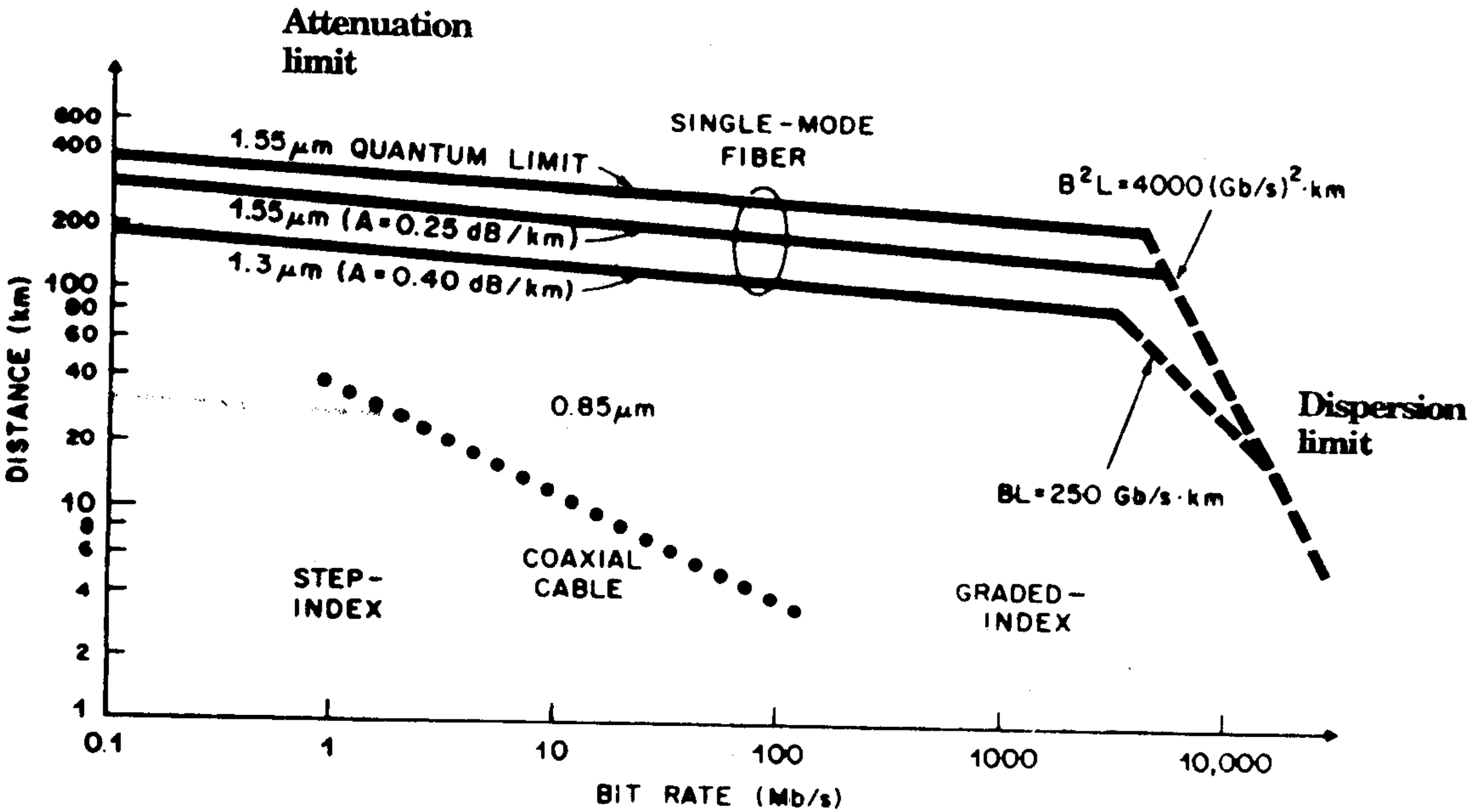
REPEATER SPACING



• DISPERSION PENALTY: POWER INCREASE NECESSARY TO RETURN THE BER TO THE REQUIRED VALUE, IN PRESENCE OF DISPERSION



REPEATER SPACING VS. BIT RATE



CSELT 27817

After: P. S. Henry, IEEE J. QE, dec. 1985