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. 405/14

SECOND WORKSHOP ON TELEMATICS

6 - 24 November 1989

Optical Fibre Overview: Propagation and Transmission Properties

R. CAPONI
CSELT, Torino, Italy

OPTICAL FIBRE OVERVIEW:

PROPAGATION AND TRANSMISSION PROPERTIES

(R. CAPONI - CSELT - TORINO)

1) <u>INTRODUCTION TO OPTICAL TRANSMISSIONS</u>:

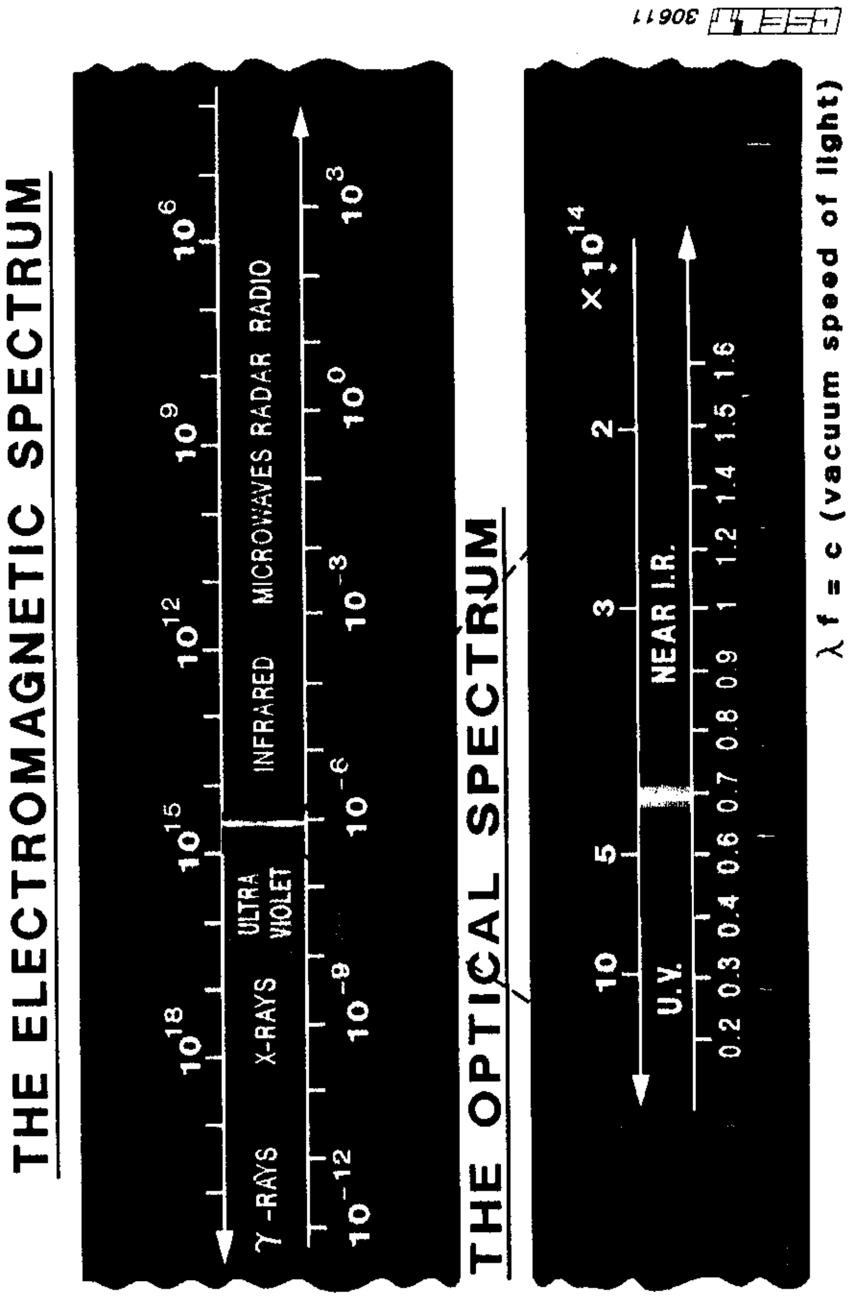
- GENERAL CHARACTERISTICS, ADVANTAGES
- THE OPTICAL FIBRE (BASIC PARAMETERS)

2) <u>FIBRE PROPAGATION</u>:

- E.M. MODES
- FIBRE TYPES { • MULTIMODE / • SINGLE MODE
- NORMALIZED FREQUENCY

3) <u>BASIC O.F. TRANSMISSIVE PROPERTIES</u>:

- ATTENUATION
- DISPERSION



WHY OPT[illegible] COMMUNIC[illegible]

- E[illegible]
  - ENORMOUS MODULATION [illegible] AVAILABLE
- AVA[illegible]
  - VERY LOW ATTENUATION MEDIUM (WITH [illegible] ATIONS)
- AVAILA[illegible] UCTOR LASE[illegible] (L[illegible]
  - POWERFUL, COMPACT AND RELIABLE SOUR[illegible]

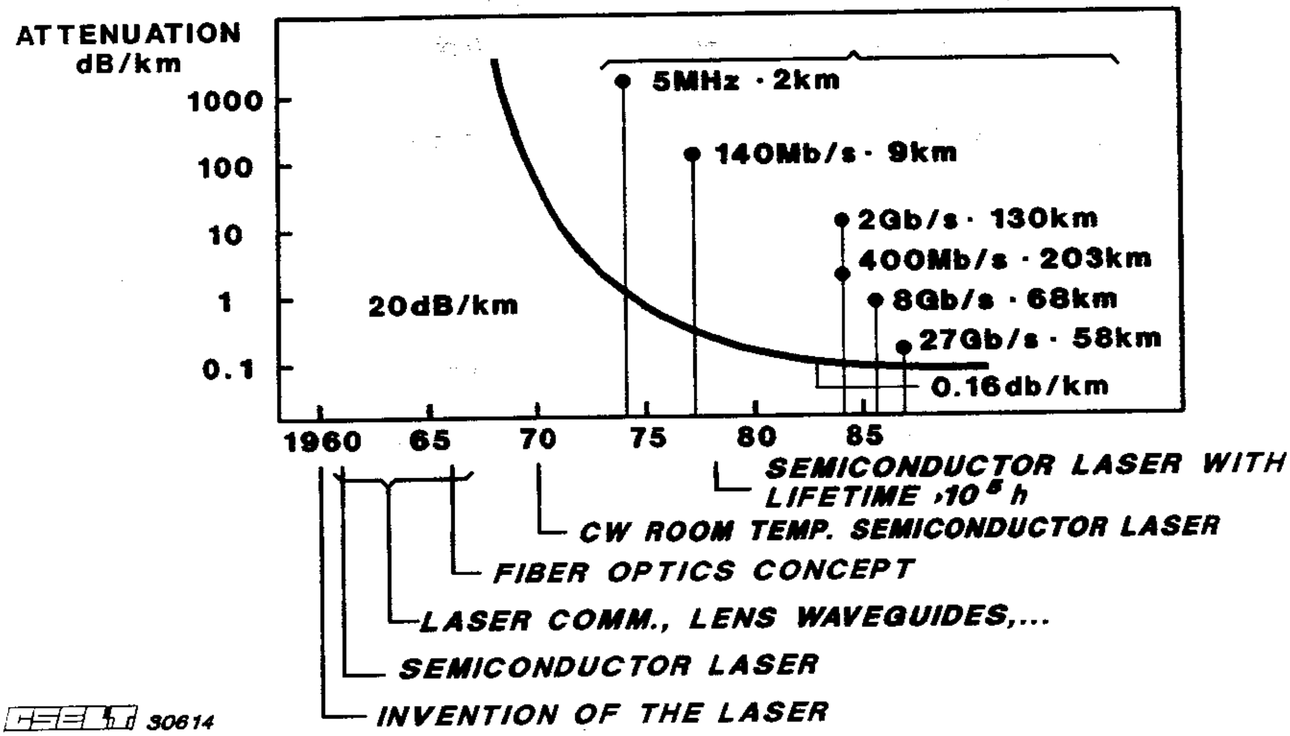
[illegible] SEVERAL [illegible]

[illegible] RS [illegible]

ADVATAGES OF OPTICAL FIBRES

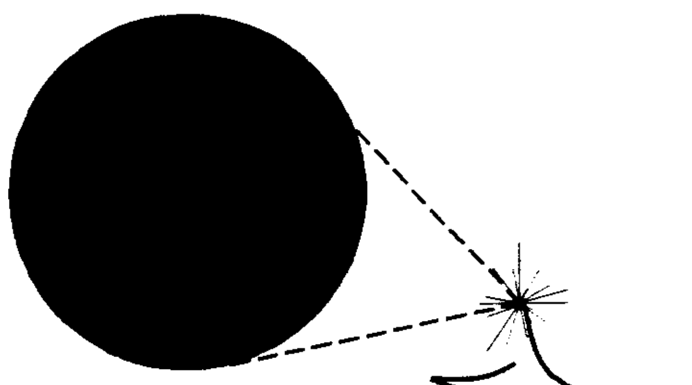
- LOW ATTENUATION
- LARGE BANDWIDTH
- SMALL DIMENSIONS AND WEIGHT
- E.M. IMMUNITY
- APPLICATION VERSATILITY
- POTENTIALLY LOWER COSTS

DEVELOPMENT OF OPTICAL COMMUNICATIONS



CSELT 30614

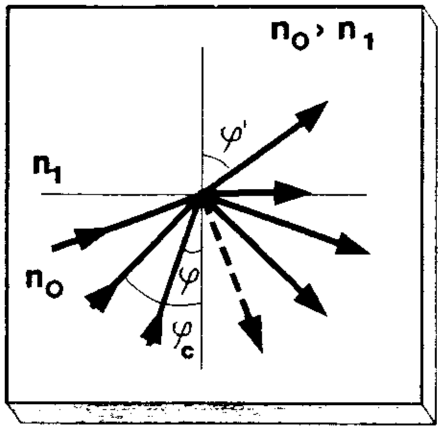
THE OPTICAL FIBRE



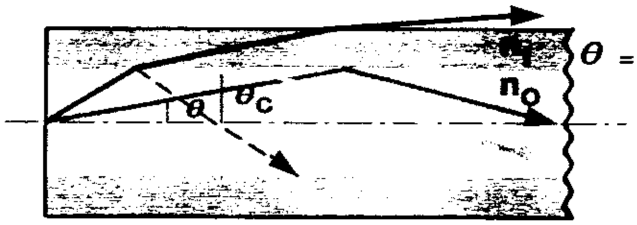
	REFRACTIVE INDEX	DIAMETER
CLADDING	n_1 - 1.46	≃125 μm
CORE	n_1+5–10‰	~5–10;50 μm

CSELT 30624

TOTAL INTERNAL REFLECTION



- SNELL'S LAW: $n_o \sin\varphi = n_1 \sin \varphi'$
- LIMITING CONDITION: $\varphi' = 90° \rightarrow n_o \sin \varphi_c = n_1$
- TOTAL REFLECTION RANGE: $\varphi > \varphi_c$



LIMITING ANGLE FOR GUIDED RAYS:

$\theta = 90° - \varphi$: $\theta_c = 90° - \varphi_c \rightarrow \cos \theta_c = \frac{n_1}{n_o}$

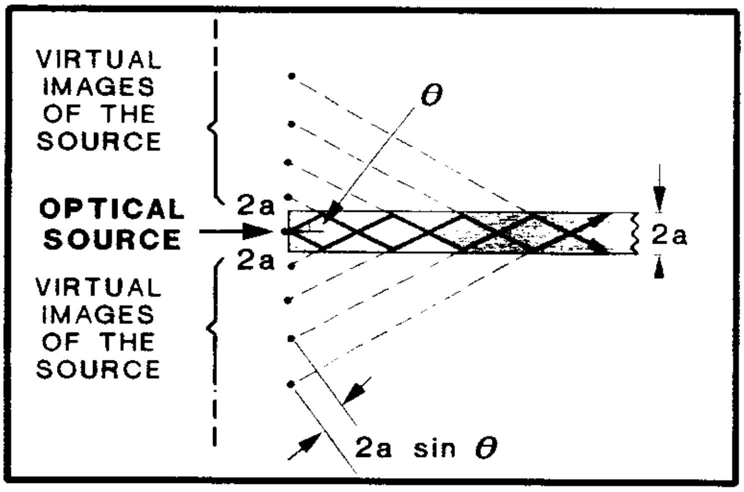
GUIDED RAY (TOT. INTERNAL REFLECTION): $\theta < \theta_c$

NUMERICAL APERTURE: $A = n_o \sin \theta_c$

$A = \sqrt{n_o^2 - n_1^2} \doteq \sqrt{2\, n_1 (n_o - n_1)}$ (TYPIC.: $A \doteq 0.1$–0.2)

CSELT 30623

A RAY-OPTICAL APPROACH TO E.M. MODES



THE PLANAR (MIRROR) WAVEGUIDE MODEL

EQUIVALENCE WITH A GRATING OF PERIOD: 2a

DIFFRACTION AND INTERFERENCE DETERMINE GUIDANCE CONDITION

ONLY THE RAYS UNDERGOING A CONSTRUCTIVE INTERFERENCE ARE ALLOWED TO PROPAGATE (grating equation)
that is: $2a \cdot \sin \theta = m \cdot \lambda$ $(m = 0,1,2,\ldots)$

ONLY DEFINITE E.M. CONFIGURATIONS - LABELLED BY INTEGER(S) - PROPAGATE IN A WAVEGUIDE:
E.M. MODES

CSELT 30622

GUIDED MODES

• DIELECTRIC GUIDE (SLAB):

$v_{MEDIUM} < c_{(FREE\ SPACE)}$ $\quad \left(\Rightarrow n = \frac{c}{v} > 1\right)$

⬇

$\lambda = \frac{\lambda_{(F.S.)}}{n} < \lambda_{(F.S.)}$ replaces λ in relev. eqs.

There fore :

① mode eq. (approx.!) : $2a \sin\vartheta = m\lambda = m\lambda/n$

② guidance condition : $n \sin\vartheta \le A$

⬇

$$\begin{cases} \vartheta = \vartheta_m \\ m\lambda = 2an \sin\vartheta_m \le 2aA \end{cases}$$

CONCLUSION : The m-th mode is guided if:

$2\pi a A > m\cdot\pi$

RADIAL PART of the FIELD:

$$\vec{E}(r) = \vec{E}_t(r) + \hat{z} E_z$$
$$\vec{H}(r) = \vec{H}_t(r) + \hat{z} H_z$$

$$\boxed{\text{SCALAR WAVE EQUATION: } \vec{E}_t \to \phi(r) \qquad \phi''(r) + \frac{\phi'(r)}{r} + \left[\left(\frac{2\pi}{\lambda}\right)^2 n^2(r) - \beta^2 - \left(\frac{\nu\pm1}{r}\right)^2\right]\phi(r) = 0}$$

$$\begin{cases} E_z = -\frac{i}{k}\left(E_r' \pm \frac{\nu\pm1}{r} E_r\right) \\ H_z = -\frac{i}{k}\left(H_r' \pm \frac{\nu\pm1}{r} H_r\right) \end{cases} \qquad \left[k(r) = \frac{2\pi}{\lambda} n(r)\right]$$

$$E_r(r) = \begin{cases} A_0 \phi_0(r), & r < a \qquad |\phi_0(0)| < \infty \\ A_1 \phi_1(r), & r > a \qquad |\phi_1(\infty)| < \infty \end{cases}$$

CONTINUITY CONDITIONS at $r = a$:

$$\frac{\phi_0'(a)}{\phi_0(a)} = \frac{\phi_1'(a)}{\phi_1(a)}$$ CHARACTERISTIC EQUATION

FOR EACH ν-VALUE → TWO FAMILIES OF SOLUTIONS:

[$\nu \pm 1$] [redacted] (UPPER SIGN)

[redacted] (LOWER SIGN)

MODE DEGENERACY : LP MODES

- $HE_{\nu+1\,\delta}$ and $EH_{\nu-1\,\delta}$ FOLLOW THE SAME EQUATION

➡ THEY HAVE THE SAME β and PROPERTIES

COMPOSED MODE :

[redacted]

LINEARLY POLARIZED

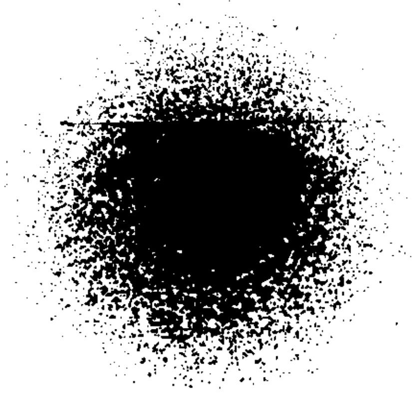
- $\nu=0$ ONLY ONE MODE $LP_{0\delta} \equiv HE_{1\delta}$

- $\nu=1$ THREE MODES COMBINED :

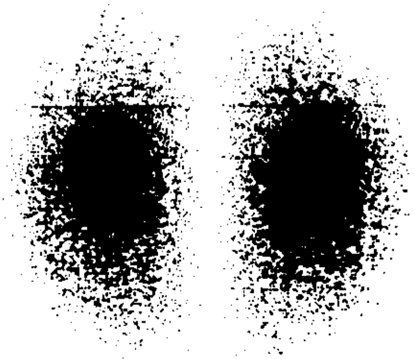
$$LP_{1\delta} \equiv \begin{cases} HE_{2\delta} + TE_{0\delta} \\ HE_{2\delta} + TM_{0\delta} \end{cases}$$

PHYSICAL MEANING OF ν and δ

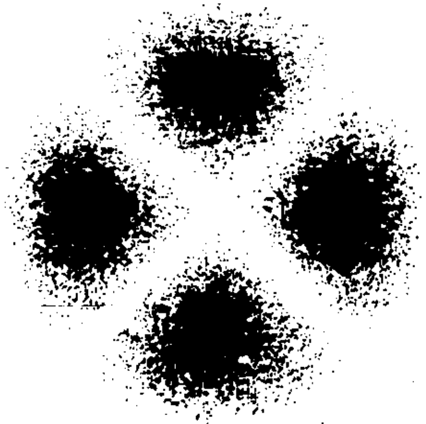
- 2ν NUMBER OF MAXIMA OF THE FIELD INTENSITY IN A TURN AROUND THE FIBRE AXIS
- δ NUMBER OF MAXIMA OF THE FIELD INTENSITY



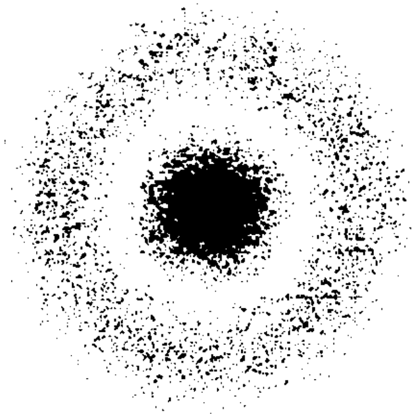
LP_{01}



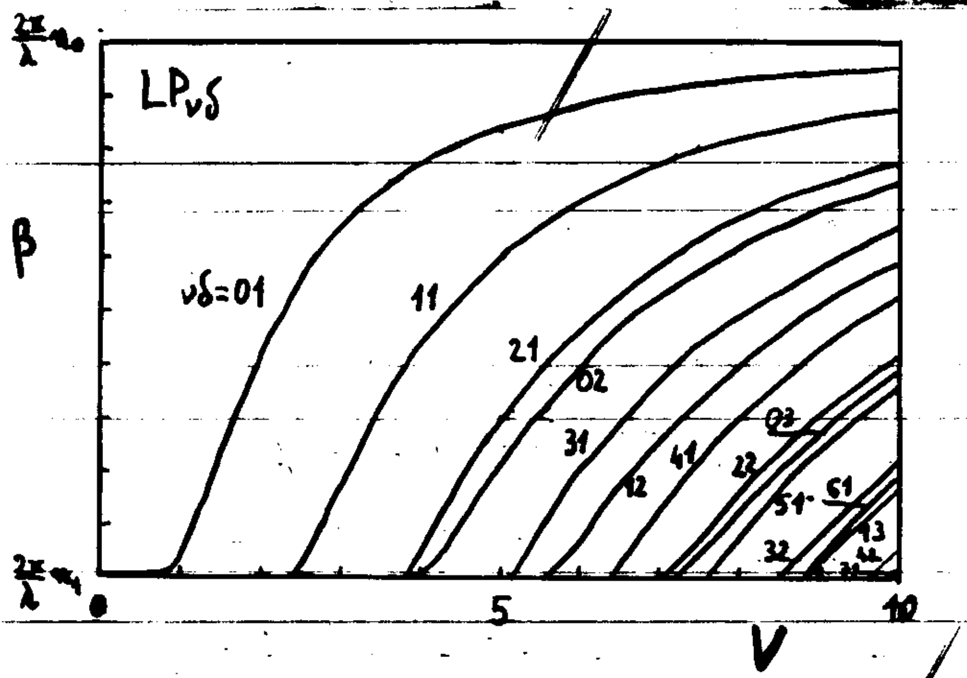
LP_{11}



LP_{21}



LP_{02}



CUT-OFF

$LP_{\nu\delta}$ MODE IS GUIDED ONLY IF:

$$V > V^{co}_{\nu\delta} \quad \text{or} \quad \lambda < \lambda^{co}_{\nu\delta} = \frac{2\pi a A}{V^{T}_{\nu\delta}}$$

[redacted] CUT-OFF WAVELENGTH OF $LP_{\nu\delta}$ MODE

IF $V < V^{co}_{11}$ $(\lambda > \lambda^{co}_{11})$ FIBRE GUIDES ONLY

[redacted] : FUNDAMENTAL MODE

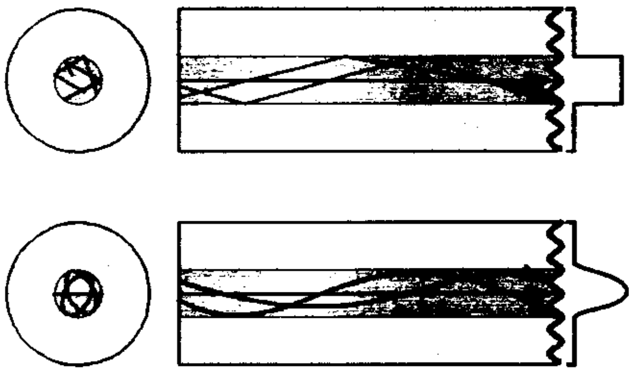
NORMALIZED FREQUENCY:
$V = \frac{\pi}{\lambda}$.(CORE DIAMETER).(NUMERICAL APERTURE)

➡ No. GUIDED MODES $\propto V^2$

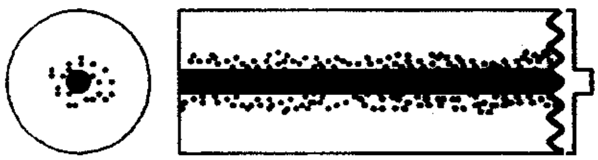
30609

FIBRE TYPES

MULTIMODE FIBRE



SINGLE-MODE FIBRE



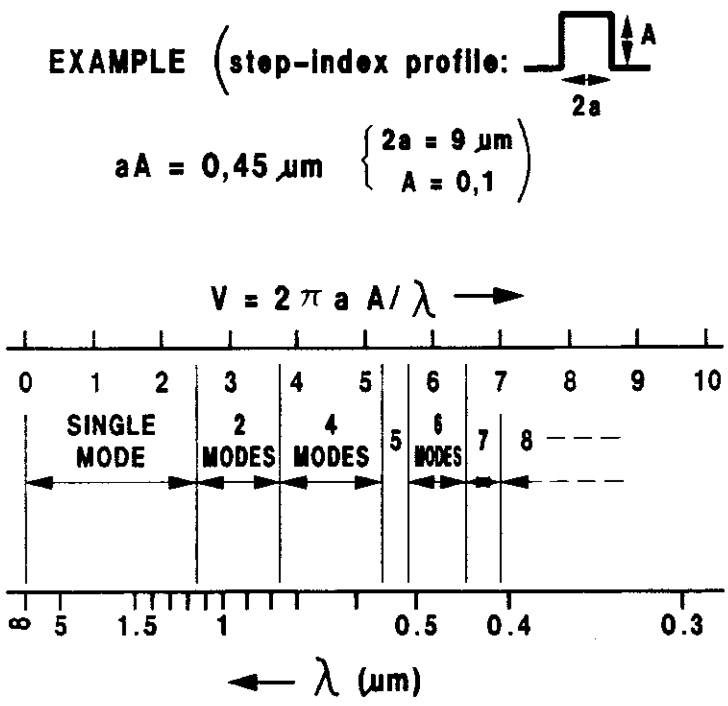
CSELT 30621

CUT-OFF V-VALUES OF THE LOWEST ORDER MODES

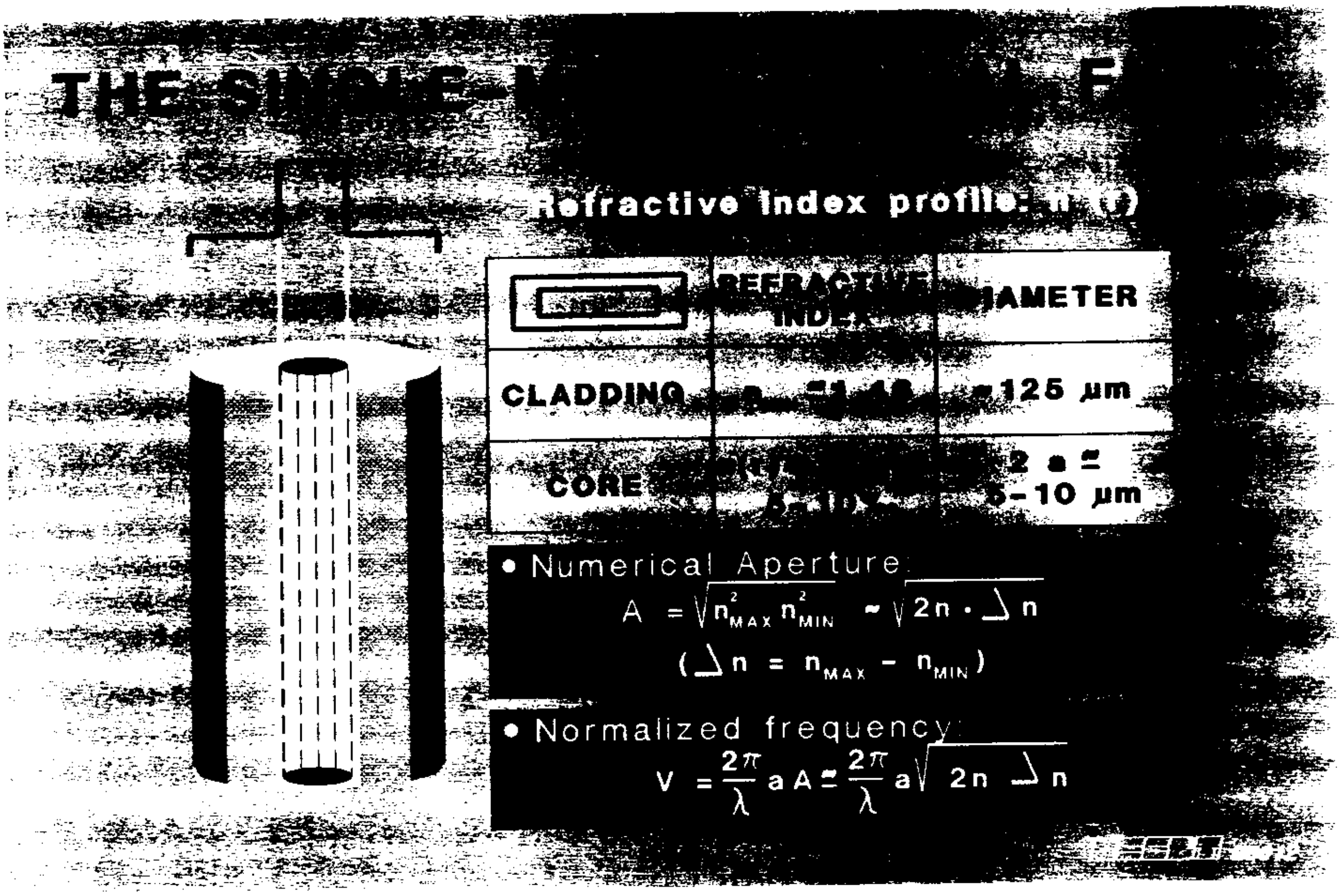
MODES LP_{nl}	$V_{CUT-OFF}(LP_{nl})$ STEP PROFILE	PARABOLIC PROFILE
LP_{01}	0	0
LP_{11}	2.4	3.5
LP_{02}	3.8	5.1
LP_{21}	3.8	5.7
LP_{31}	5.1	7.8
LP_{12}	5.5	7.5
LP_{41}	6.4	9.9
LP_{03}	7.0	9.2

EXAMPLE (step-index profile:

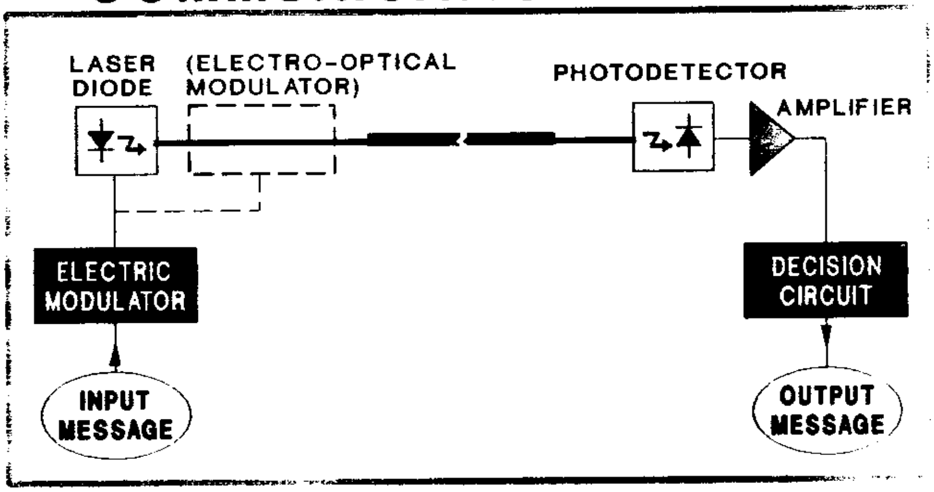
$aA = 0{,}45\ \mu m$ $\left\{\begin{array}{l} 2a = 9\ \mu m \\ A = 0{,}1 \end{array}\right)$



CSELT 30608



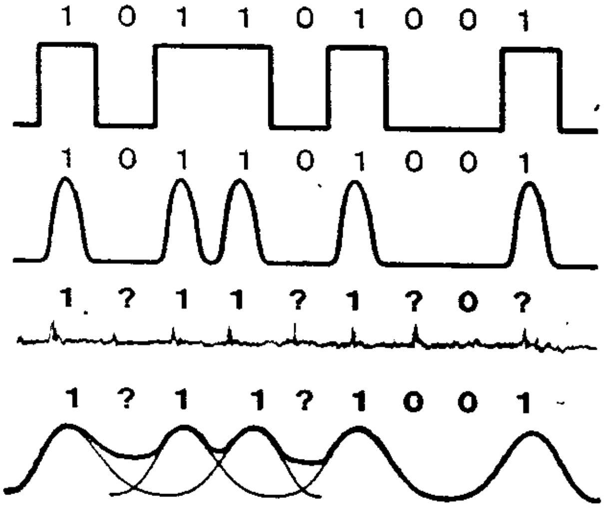
SCHEME OF A FIBRE-OPTIC COMMUNICATION SYSTEM



SYSTEM PERFORMANCE:
- REPEATER SPACING
- TRANSMISSION BANDWIDTH

CORRESPONDING FIBRE PROPERTIES:
- TOTAL ATTENUATION
- PULSE DISTORTION

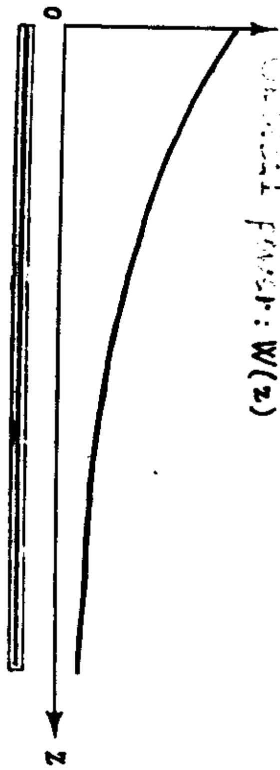
INFORMATION LOSS DUE TO ATTENUATION AND DISPERSION



OUTPUT SIGNAL SEPARATED FROM NOISE:
→ *MAX. ATTENUATION ALLOWED*

ADJACENT PULSES DISTINGUISHED IN TIME:
→ *MAX. DISPERSION ALLOWED*

ATTENUATION



$$W(z) = W_0 e^{-\alpha z}$$ (from experiment) ⇒

$$\boxed{\alpha = \frac{10}{z_2 - z_1} \log \frac{W(z_1)}{W(z_2)}}$$ ⇒ (in dB only)

⇓

DEFINITION OF THE ATTENUATION COEFFICIENT in dB/km.

EXTRINSIC SOURCES OF ATTENUATION

● ION ABSORTION

TRANSITION METAL IMPURITIES: $\begin{cases} Fe^{++}, Ne^{+++}, Cu^{++} \\ Cr^{+++}, Mn^{+++}, V^{+++} \end{cases}$

EXCESS ATTENUATION.: 1-5 dB/km FOR 1 ppb

OH^- GROUP IMPURITIES

3 PEAKS AT 0.94 , 1.24, 1.38 um WITH RESPECTIVE

EXCESS ATTENUATIONS.: 1, 1.4, 70dB/km FOR 1 ppm

● OPTICAL AND GEOMETRIC ANOMALIES

CORE DIAMETER/NUMERICAL APERTURE FLUCTUATIONS, FIBRE NON-CIRCULARITY AND FABRICATION DEFECTS IN GENERAL

● MICROBENDING

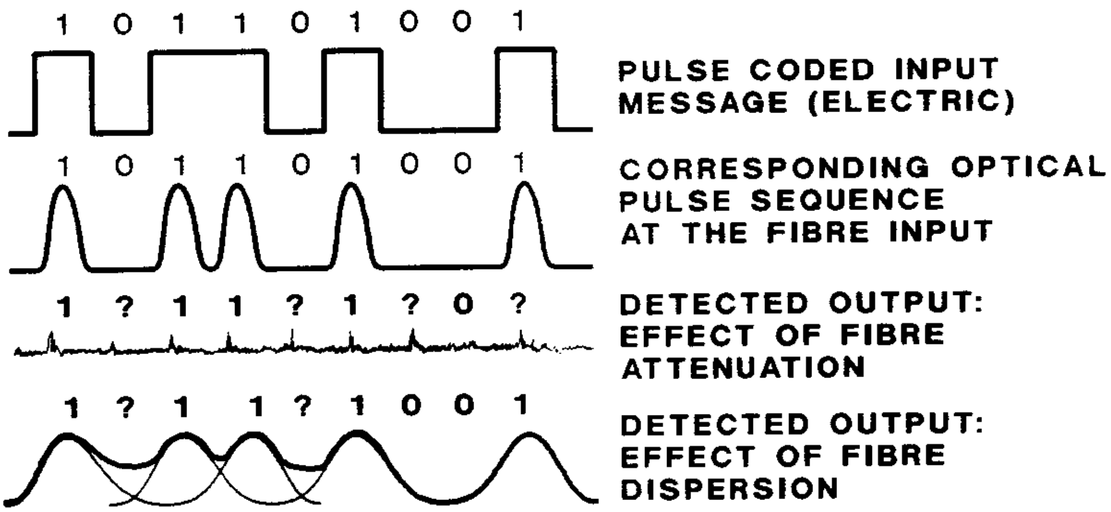
DUE TO CABLING OPERATIONS

● BENDING

FROM SPLICES, CONNECTORS, INSTALLATION

CSELT 30617

INFORMATION LOSS DUE TO ATTENUATION AND DISPERSION



OUTPUT SIGNAL SEPARATED FROM NOISE:

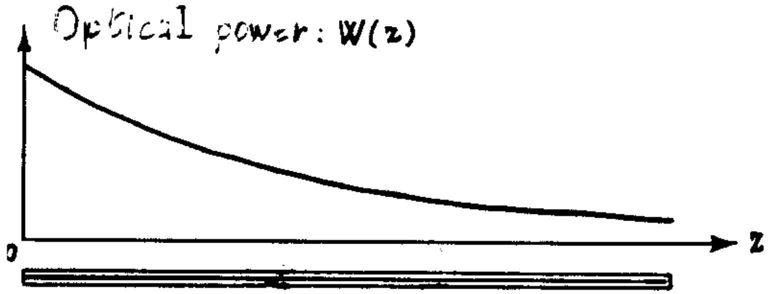
→ *MAX. ATTENUATION ALLOWED*

ADJACENT PULSES DISTINGUISHED IN TIME:

→ *MAX. DISPERSION ALLOWED*

CSELT 30619

ATTENUATION



$W(z) = W_0 e^{-\alpha z}$ (pure exponential $\Rightarrow$

$\Rightarrow$ ONE MODE ONLY)

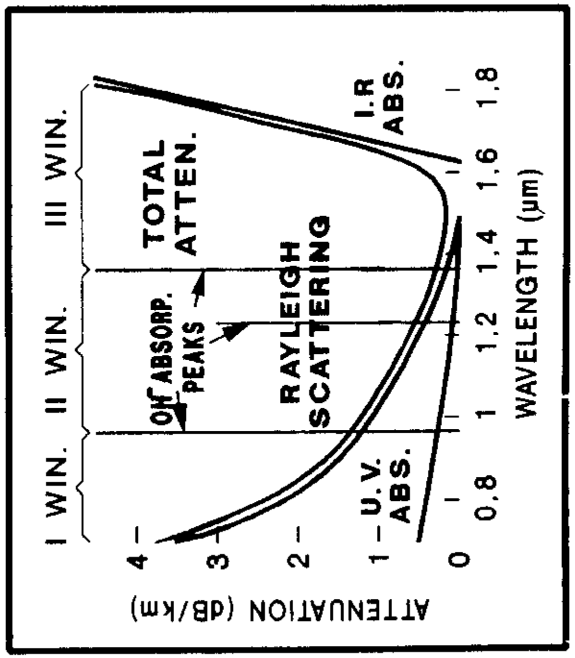
$$\boxed{\alpha = \frac{1}{z_2 - z_1} \mathrm{Log}_{10} \frac{W(z_2)}{W(z_1)}}$$

$\Downarrow$

DEFINITION OF THE ATTENUATION COEFFICIENT in dB/km

ATTENUATION INTRINSIC SOURCES

- DEPENDENT ON GLASS COMPOSITION AND STRUCTURE
- UNAVOIDABLE



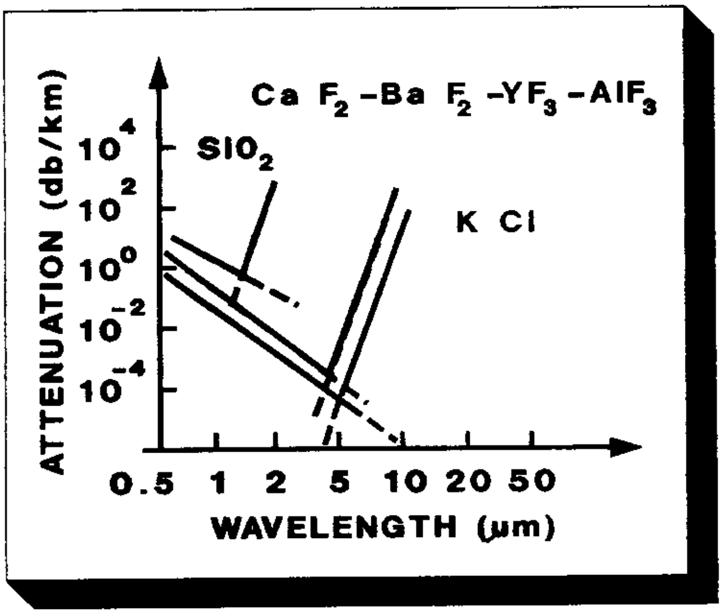
RAYLEIGH SCATTERING
(DENSITY FLUCTUATIONS AT THE MOLECULAR LEVEL)

UV ABSORPTION
(ELECTRONIC TRANSITIONS)

IR ABSORPTION
(MOLECULAR TRANSITIONS)

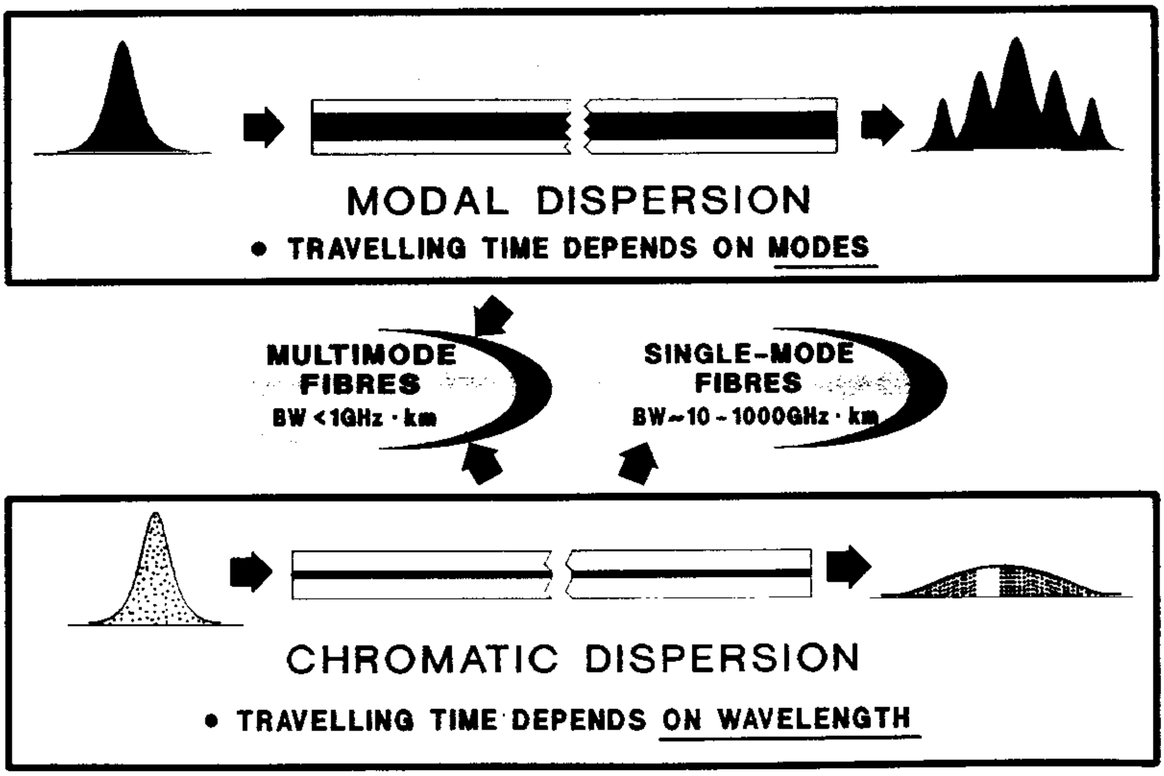
30618

POSSIBLE ATTENUATION WITH DIFFERENT MATERIALS FOR MID-I.R.



30630

SOURCES OF PULSE DISPERSION

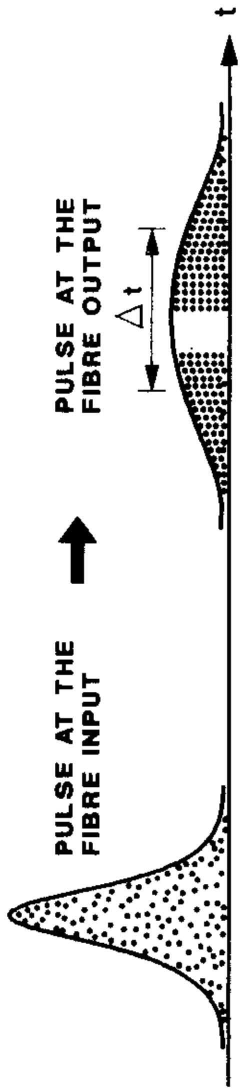


30616

CHROMATIC DISPERSION

(TRAVELLING TIME DEPENDS ON λ)

- THE ONLY SOURCE OF DISPERSION IN SINGLE-MODE FIBRES -



τ : TRAVELLING TIME OVER 1 km FIBRE LENGTH

$D = d\tau / d\lambda$: *CHROMATIC DISPERSION*

$$\boxed{\Delta t = L \cdot \Delta\lambda \cdot D}$$

L : FIBRE LENGTH

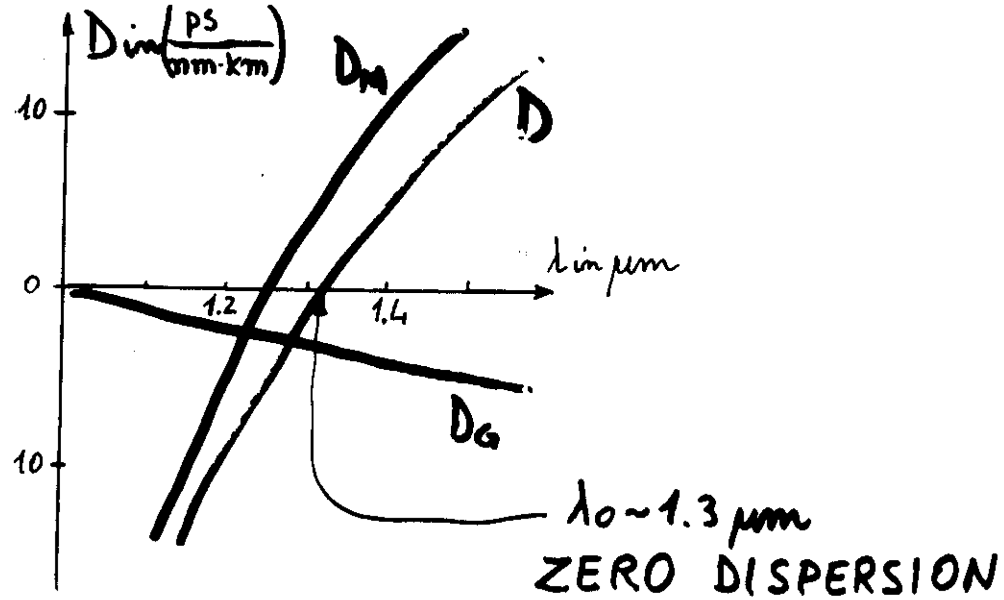
$\Delta\lambda$: SOURCE SPECTRAL LINEWIDTH

30645

- τ DEPENDS on λ:
  1. THROUGH THE GUIDE EFFECT
  2. BECAUSE THE MATERIAL IS DISPERSIVE ($n = n(\lambda)$)

→ D HAS TWO CONTRIBUTIONS:

1. GUIDE DISPERSION : D_G
2. MATERIAL DISPERSION: D_M



BANDWIDTH

$$p_{out} = g(t) * p_{in}(t)$$

$$P_{out}(\omega) = G(\omega)\ P_{in}(\omega)$$

$$G(\omega) = \int_{-\infty}^{+\infty} g(t)\ \exp(-i\omega t)\ dt$$

$$\sigma_f^2 = \sigma_{out}^2 - \sigma_{in}^2$$

$$B(GHz) = 0.187/\sigma_f(ns)$$

BANDWIDTH OF SINGLE-MODE FIBRE TRANSMISSIONS

	λ (μm)	D [ps/(nm · km)]	BW (GHz · km)
MULTIMODE LASER $\Delta\lambda \sim 2$ nm	1.3 1.5	~1 ~10	~100 ~10
SINGLE-MODE LASER $\Delta\lambda \sim 0.1$ nm	1.3 1.5	~1 ~10	~2000 ~200

CSELT 30815

index profile										
dispersion [ps/nm km]	-1	0	0	-6	-	-	0.3	3	0	0
slope [ps/nm2 km] at 1.55 µm	0.08	0.06	0.05	0.154	-	-	0.052	0.09	0.075	-
zero disp [µm]	1.56	1.55	1.55	1.59	1.56	1.56	1.544	1.52	1.55	1.55
reproducibility [µm]	-	-	-	-	-	± 0.01	±0.022	-	± 0.01	-
loss [dB/km] at 1.55 µm	0.32	0.2	0.20	0.2	0.33	0.21	0.24	0.21	0.21 (0.17)	0.22
splice loss [dB]	.	-	0.04 ±0.03	-	-	0.06	-	-	0.12	-
manufacturing process	VAD	VAD	VAD	VAD	MCVD	MCVD	MCVD	VAD	OVD	MCVD
year	1982	1982	1986	1986	1984	1983/84	1985	1985	1985/86	1984
literature	[27]	[28]	[15]	[10]	[8]	[7,22,23]	[14]	[9]	[12, 13]	[11]

status of dispersion shifted SM - fibres

(FROM P.K. BACHMANN ECOC'86)

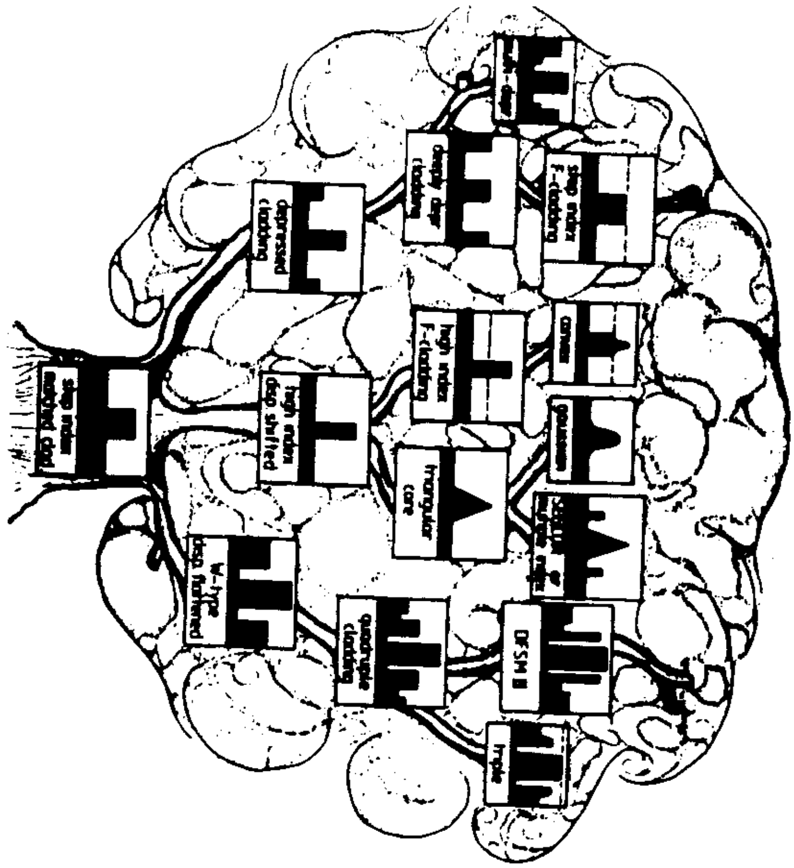
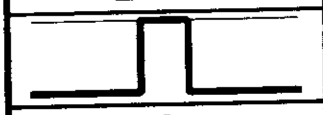
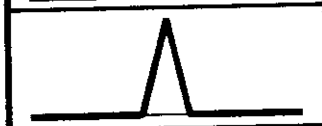
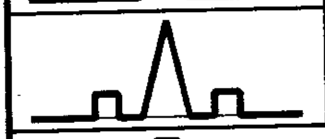
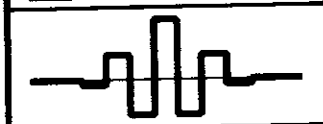


fig. 3: family tree of single mode fibres

(FROM P. K. BACHMANN ECOC'86)

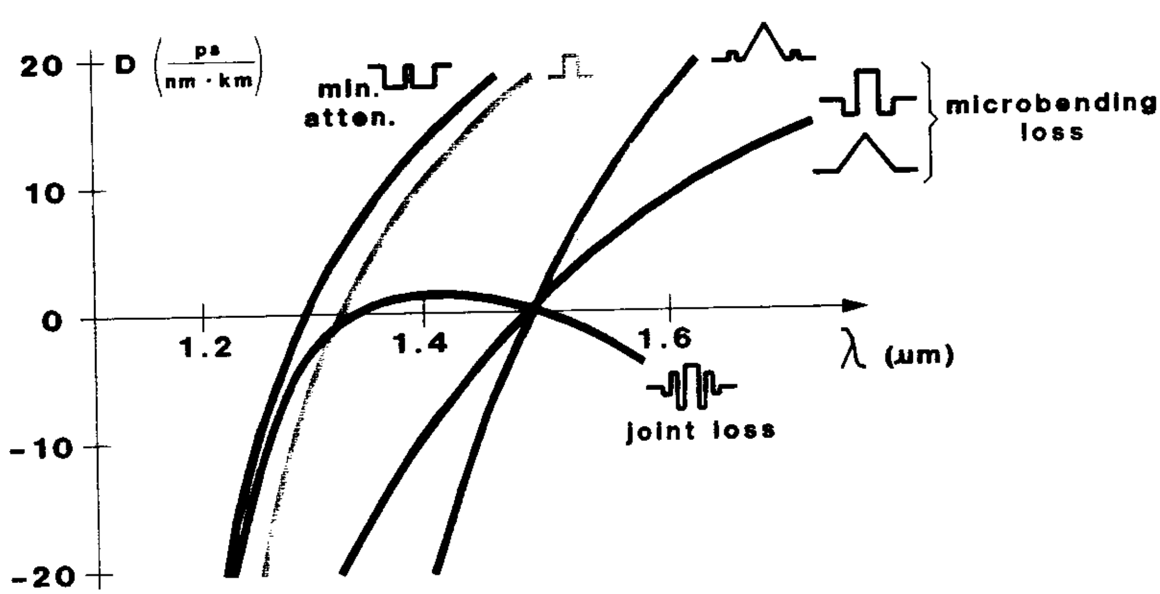
REFRACTIVE INDEX DESIGNS OF SINGLE-MODE FIBRES

	MATCHED CLADDING	1300 nm OPTIMIZED
	DEPRESSED CLADDING	LOWER BEND LOSSES
	"W" TYPE	DISPERSION MODIFIED
	PURE SILICA CORE	MINIMUM ATTENUATION
	TRIANGULAR CORE	1550 nm OPTIMIZED
	SEGMENTED CORE	1550 nm OPTIMIZED LOWER BEND LOSSES
	QUADRUPLE CLADDING	DISPERSION FLATTENED

[———— SiO_2 LEVEL]

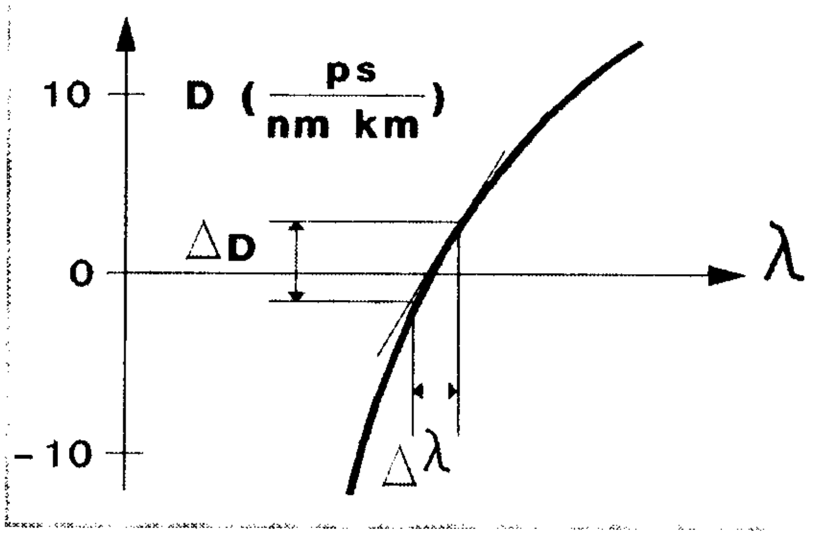
30613

DISPERSION OPTIMIZATION



30644

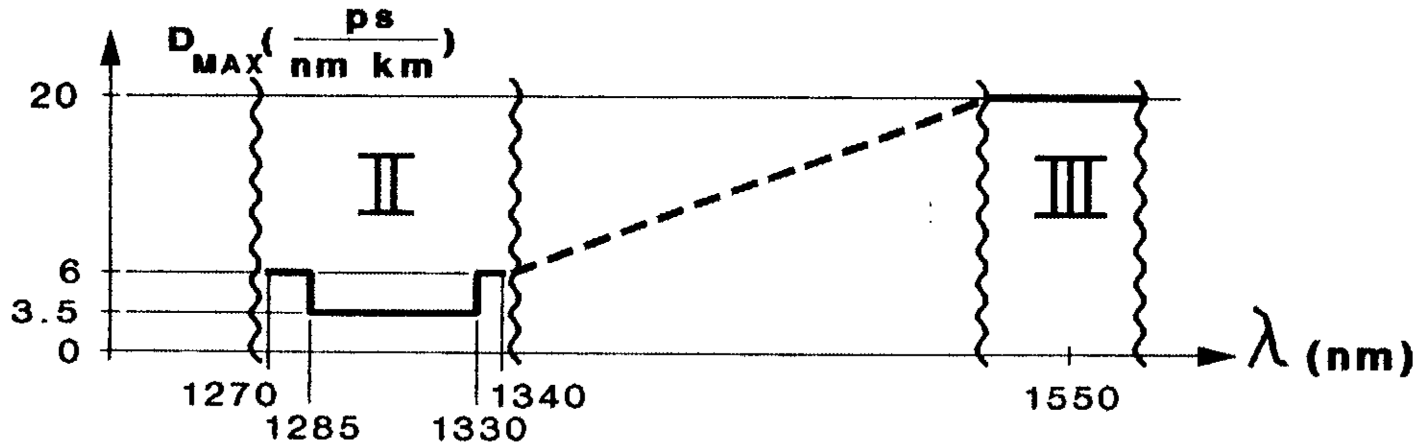
CHROMATIC DISPERSION (CCITT STANDARD)



λ_o : zero dispersion wavelength

$S_o = \left.\frac{\Delta D}{\Delta \lambda}\right|_{\lambda = \lambda_o}$ D slope at $\lambda = \lambda_o$

- $\lambda_{o\,MIN}$ = 1295 nm ; $\lambda_{o\,MAX}$ = 1322 nm ; $S_{o\,MAX}$ = 0,095 $\frac{ps}{nm^2\,km}$
- **Equivalent to:**



30628