INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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SECOND WORKSHOP ON
OPTICAL FIBRE COMMUNICATION
(14 - 25 March 1988)

# CHARACTERIZATION OF OPTICAL FIBRES

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## SINGLE-MODE FIBER MEASUREMENT ISSUES

- Precise definition of measurement parameter
- Accurate settlement of relevant measurement conditions
- Relation among different measurement techniques
- Standardization (RTM and ATM)

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## STANDARDIZATION OF TEST METHODS (CCITT)

### REFERENCE TEST METHOD (RTM)

- MAXIMUM ACCURACY
- MAXIMUM REPEATABILITY
- DIRECT AGREEMENT WITH DEFINITION
- ABSOLUTE VALIDITY

### ALTERNATIVE TEST METHOD (ATM)

- PRACTICAL
- REPEATABLE
- RELATABLE TO RTM

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## SINGLE-MODE FIBER MEASUREMENTS

### AIMS AND REQUIREMENTS

| | | |
|---|---|---|
| LABORATORY MEAS. | R&D | ACCURACY, SENSITIVITY |
| FACTORY MEAS. | QUALITY CONTROL<br>ACCEPTANCE TESTS | AUTOMATION, REPEATABILITY |
| FIELD MEAS. | TESTING<br>MAINTENANCE | HANDINESS, PRACTICABILITY |

23221

## TYPES OF SINGLE-MODE FIBERS

| 1st GENERATION | 2nd GENERATION | 3rd GENERATION |
|---|---|---|
| CONVENTIONAL STEP-INDEX (DISP. OPT. AT 1300 nm) | DISPERSION SHIFTED (AT 1550 nm) | POLARIZATION-MAINTAINING |
| | DISPERSION FLATTENED (1300-1500 nm) | |

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# MEASUREMENTS REQUIRED AT VARIOUS STAGES

| MEASUREMENT PARAMETER | FACTORY | | FIELD | |
|---|---|---|---|---|
| | FIBRE | CABLE | INSTALLATION | MAINTENANCE |
| ATTENUATION | ROUTINE | ROUTINE | ROUTINE | ROUTINE |
| CUT-OFF WAVELENGTH | ROUTINE | ROUTINE | | |
| MODE FIELD DIAMETER | SAMPLE | | | |
| CHROMATIC DISPERSION | SAMPLE | | POSSIBLE | POSSIBLE |
| GEOMETRY | SAMPLE | | | |
| REFRACTIVE INDEX PROFILE | SAMPLE | | | |
| MECHANICAL TESTS | ROUTINE | ROUTINE | | |
| SPLICES | | | ROUTINE | ROUTINE |
| FAULTS | ROUTINE | ROUTINE | ROUTINE | ROUTINE |

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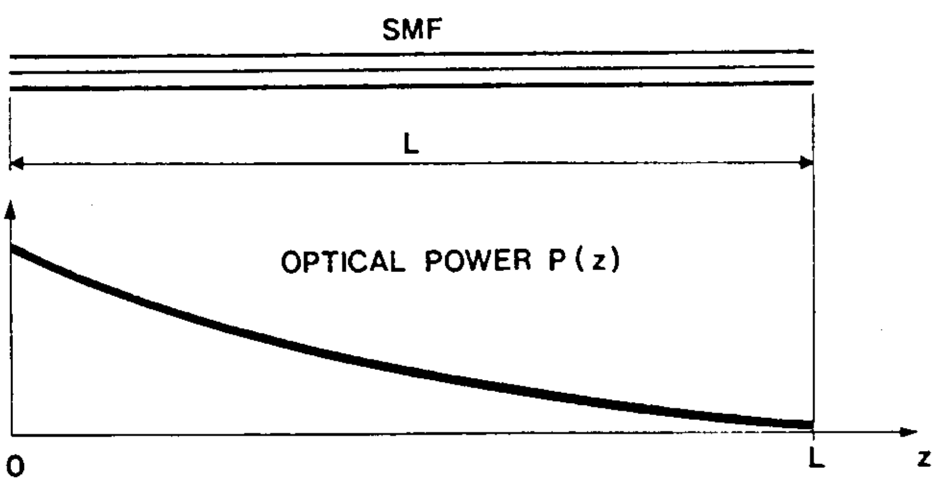
# ATTENUATION COEFFICIENT: $\alpha$
## DEFINITION




$$\alpha \text{ (dB/km)} = \frac{10}{L\text{ (Km)}} \text{Log}\left(\frac{P(0)}{P(L)}\right)$$

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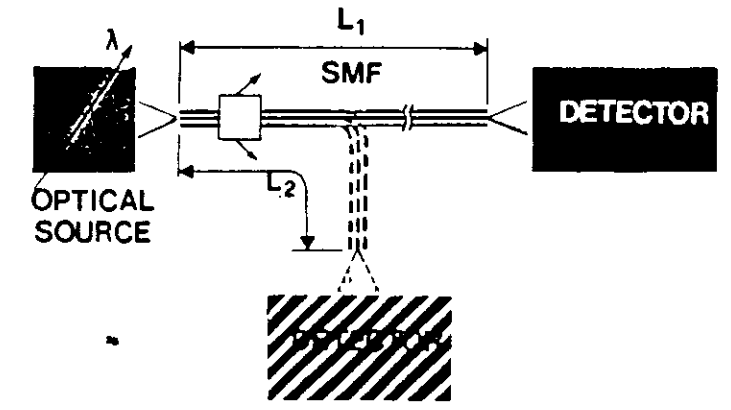
# ATTENUATION MEASUREMENT
## CUT-BACK TECHNIQUE




$$\alpha(\lambda) = \frac{1}{L_1 - L_2} \operatorname{Log} \left( \frac{P(L_2,\lambda)}{P(L_1,\lambda)} \right)$$

- (+) RTM
- (−) DESTRUCTIVE ($L_2$=1,2 m)
- (−) CLADDING MODE SUPPRESSION
- (+) NO DMA EFFECTS

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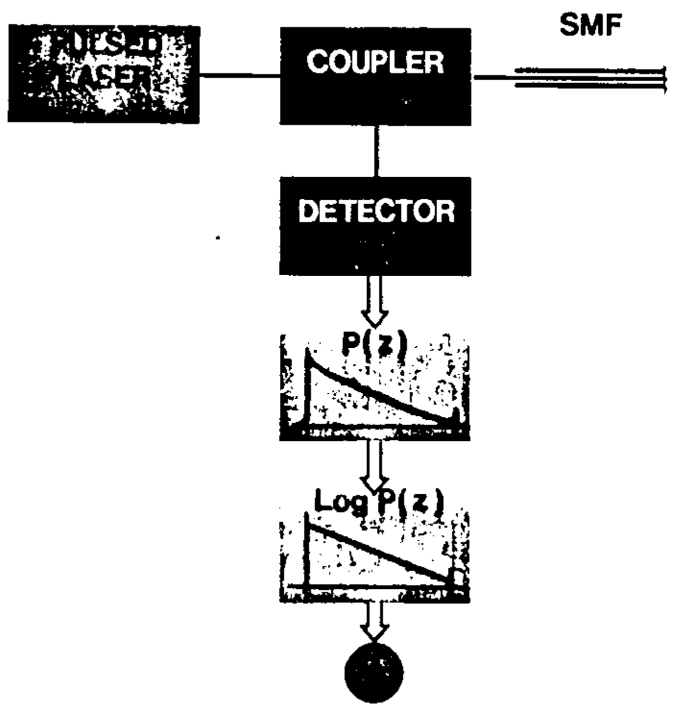
# ATTENUATION MEASUREMENTS
## BACKSCATTERING TECHNIQUE




- (−) ATM
- (+) ONE END ONLY ACCESS
- (+) NON DESTRUCTIVE
- (+) FAULT & SPLICE LOSS MEAS
- (−) POLARIZATION EFFECTS
  - POL. INSENSITIVE COUPLER
- (−) LOW POWER LEVEL
  - LOW NOISE TRANSIMP. AMPLIF.
  - COHERENT DETECTION
  - PHOTON COUNTING

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## BACKSCATTERING (OTDR)

| Tx / Rx | SINGLE PULSE | SIGNAL CODING | |
|---|---|---|---|
| | | INTENSITY MODULATION | FREQUENCY MODULATION |
| DIRECT DETECTION | C | C | |
| COHERENT | C | | L |
| PHOTON COUNTING | C | L | |

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## BACKSCATTERING METHOD

*SUMMARY*

- Specific set-ups for different applications?
  - "Traditional" applications
    - Fault location
    - Attenuation
    - Splice loss
  - "Novel" applications
    - Sensors
      - □ *spatial distribution of stress, temperature, fields, ... (use of polarization, phase)*
    - I.O. Circuits
- Laboratory research:
  - Raman fibre backscattering vs. λ

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## CUT-OFF WAVELENGTH: $\lambda_c$

**A** • Defines single-mode operation range
- — Low as much as possible to avoid:
  - Bimodal operation
  - Modal noise at joints

**B** • Rules indirectly 1550 nm performances
- — High as much as possible to allow:
  - Greater mode confinement
  - Lower bending loss

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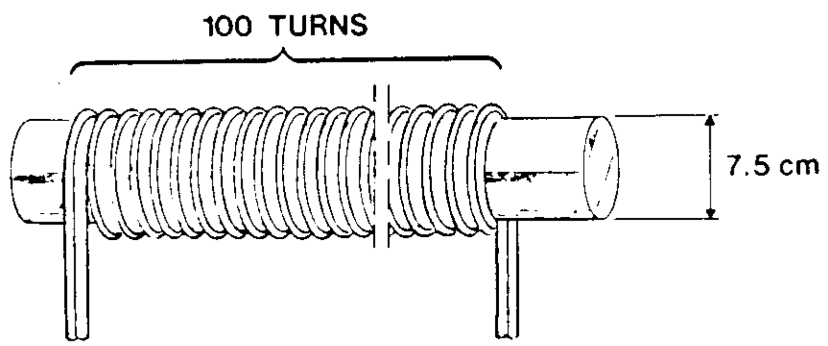
## ATTENUATION MEASUREMENT
### QUALIFICATION TEST FOR USE AT 1550nm




LOSS INCREASE AT $\lambda$ = 1550 nm LESS THAN 2dB

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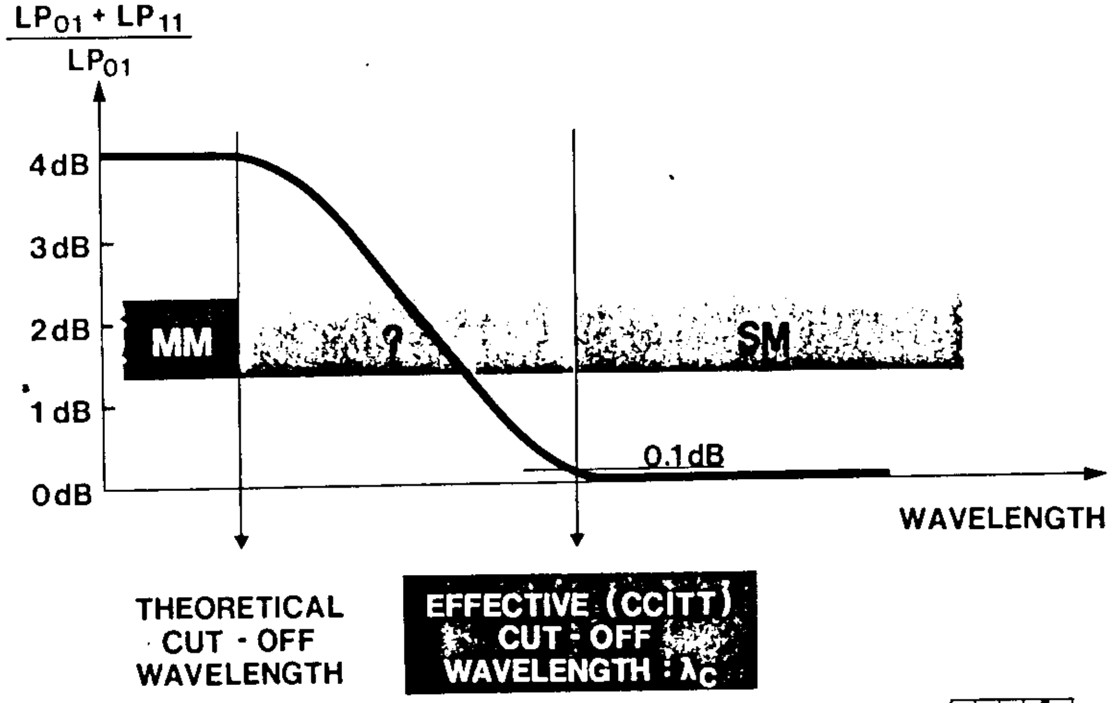
# CUT-OFF WAVELENGTH
DEFINITION

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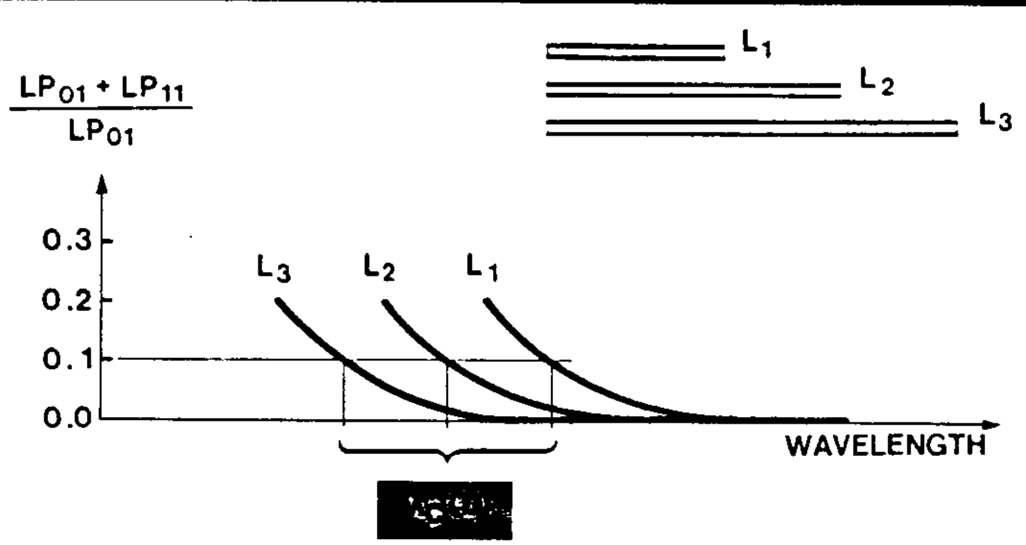
# CUT-OFF WAVELENGTH
## $\lambda_C$ VS. FIBRE LENGTH : L




MEASUREMENT STANDARD CONDITION : L = 2m

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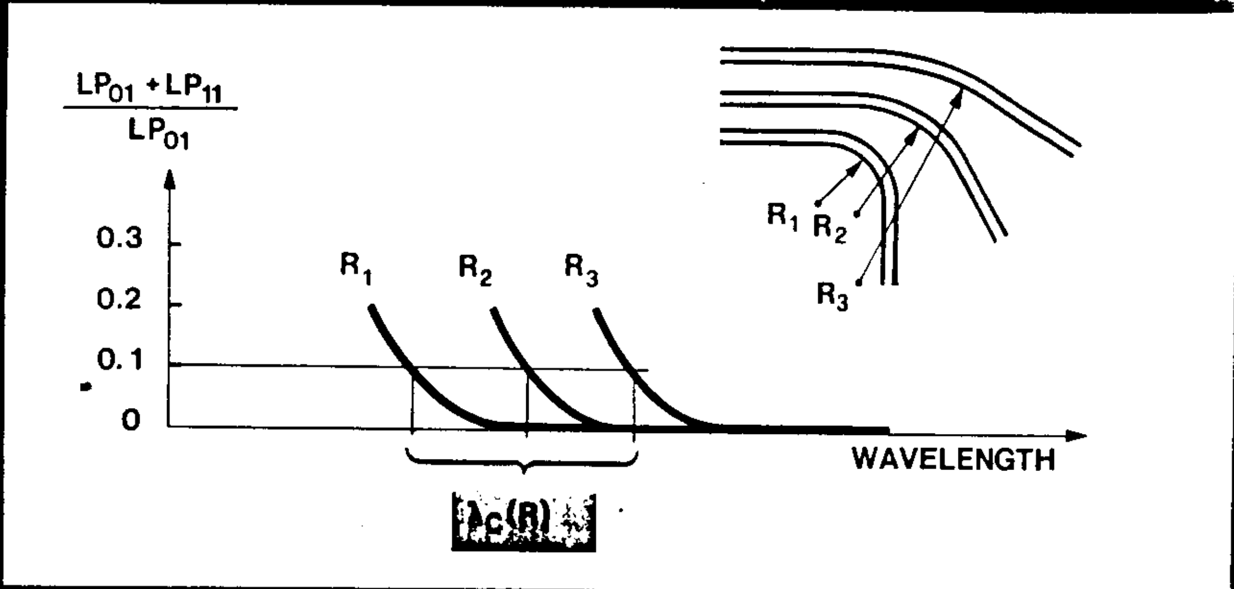
# CUT-OFF WAVELENGTH

## $\lambda_C$ VS. CURVATURE RADIUS : R




MEASUREMENT STANDARD CONDITION : R = 14 cm

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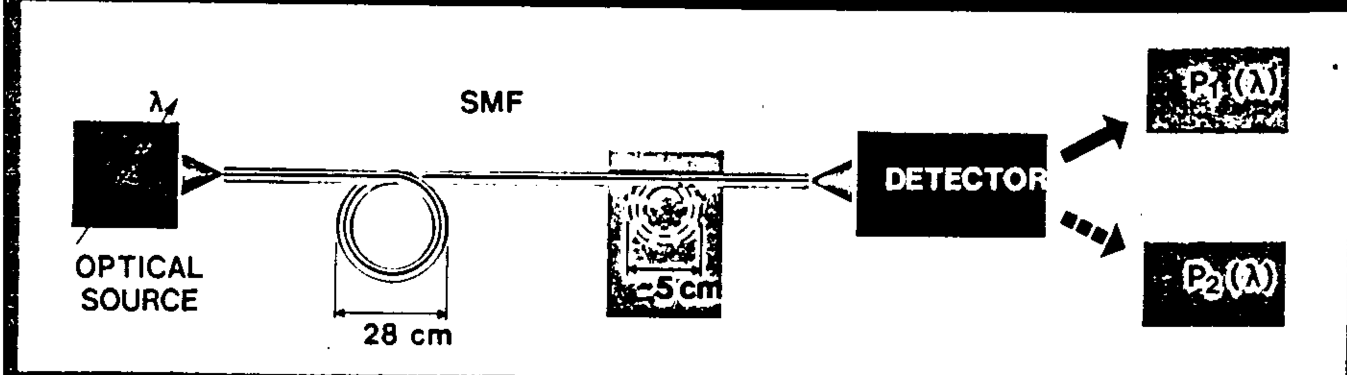
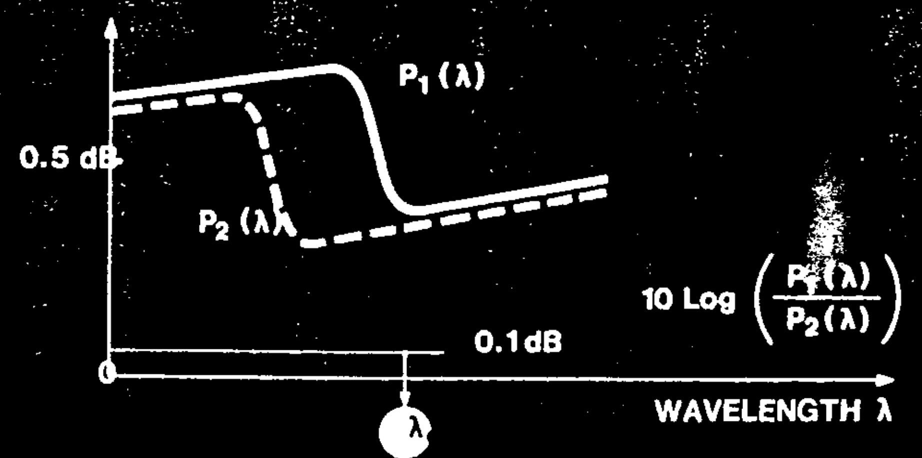
# CUT-OFF WAVELENGTH MEASUREMENTS

## RTM1: TRANSMITTED POWER TECHNIQUE: BENDING VERSION

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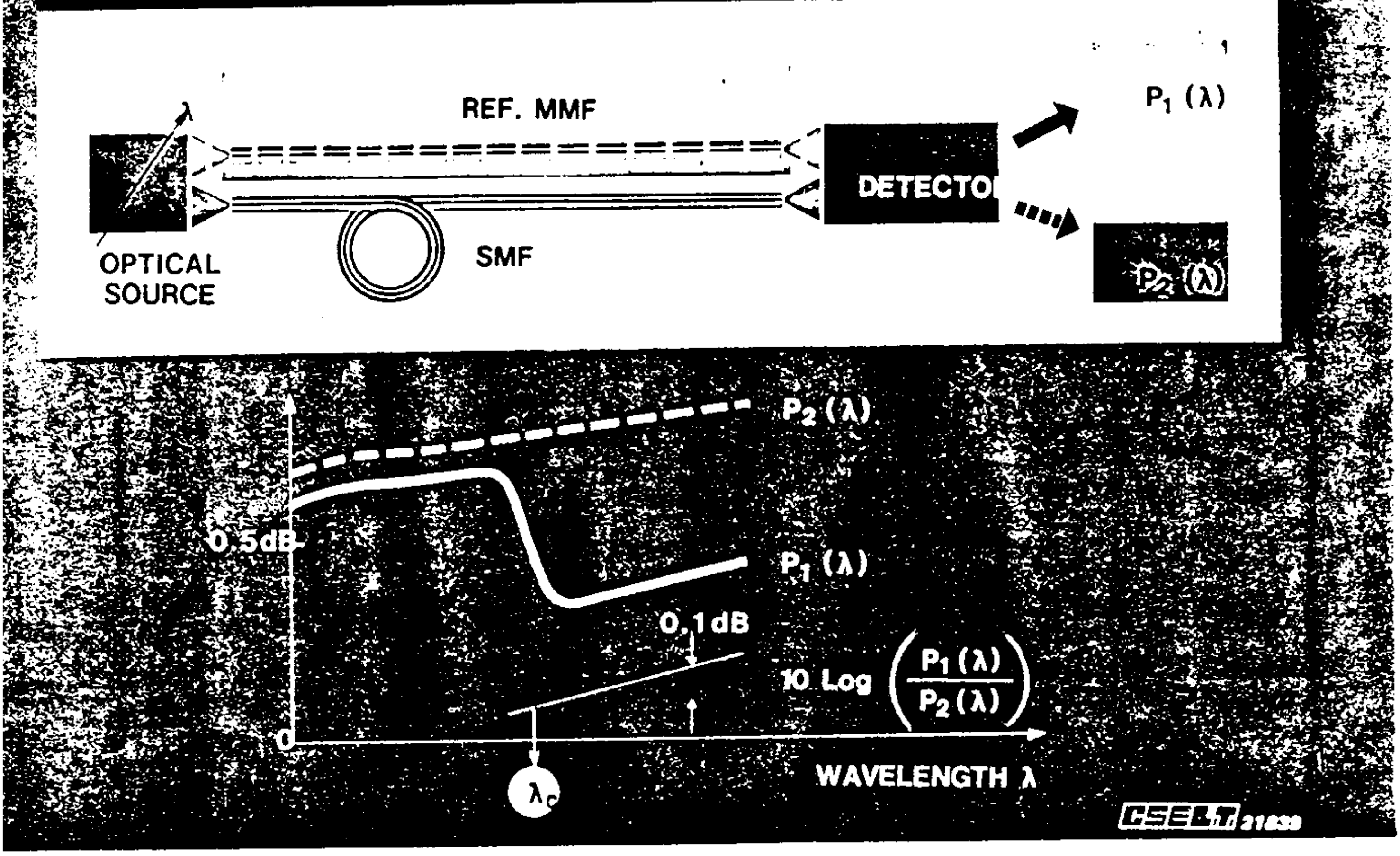
## CUT-OFF WAVELENGTH MEASUREMENTS
### RTM2: TRANSMITTED POWER TECHNIQUE: MMF VERSION

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## CUT-OFF WAVELENGTH MEASUREMENTS

### OTHER TECHNIQUES

- SPECTRAL SCANNING OF
  - MODE FIELD DIAMETER (ATM)
  - NEAR-FIELD PATTERN
  - REFRACTED NEAR-FIELD
- TECHNIQUES FOR MEAS. OF $\frac{LP_{01}+LP_{11}}{LP_{01}}$ RATIO (OR $\alpha_{11}$)
  - POLARIZATION METHOD (2 SCANS; DELICATE)
  - TWO-LENGTHS METHOD (3 SCANS; 1 CUT-BACK)
  - TWO PERTURBATIONS METHOD (3 SCANS)

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# CUT—OFF WAVELENGTH STANDARDIZATION

**CCITT RECOMMENDED RANGE**
**1100 nm $\leq \lambda_c \leq$ 1280 nm**

**PERSPECTIVES:**
**[illegible]**

| **INCREASE $\lambda_{CMAX}$** | **DECREASE $\lambda_{CMAX}$** |
|---|---|
| • Greater mode confinement | • Multiple pulses: BW reduction |
| • Lower bending loss at 1550 nm | • Modal noise: 2-mode interf. at joints |
| • Long links | • Short links, pig-tails, repair sections |

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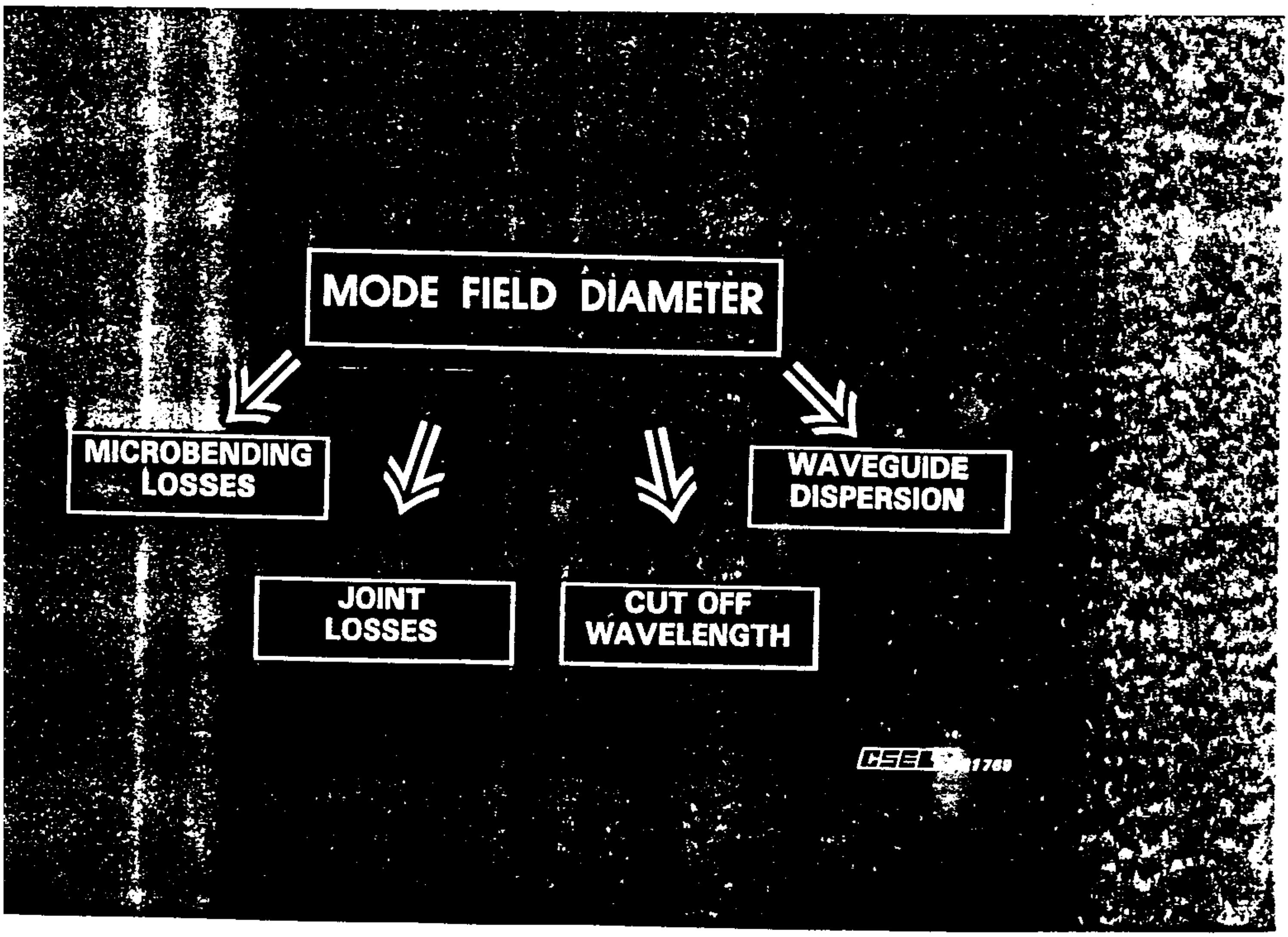
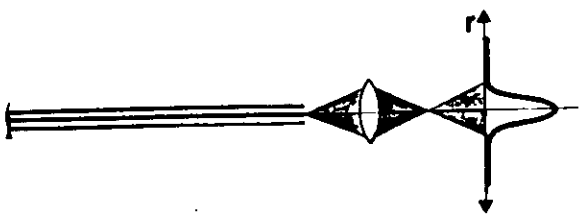


# MODE FIELD DIAMETER
## DEFINITION: $d_n$




NEAR - FIELD INTENSITY : $E^2(r)$
(NFI)

$$d_n = 2\left[2\int_0^{\infty} r^2 \cdot E^2\, r\,dr \Big/ \int_0^{\infty} E^2\, r\,dr\right]^{1/2}$$

- $\propto$ rms WIDTH OF NFI
- JOINT LOSSES FOR TILTS $\propto d_n^2$
- MICROBENDING LOSSES $\propto d_n^{10}$

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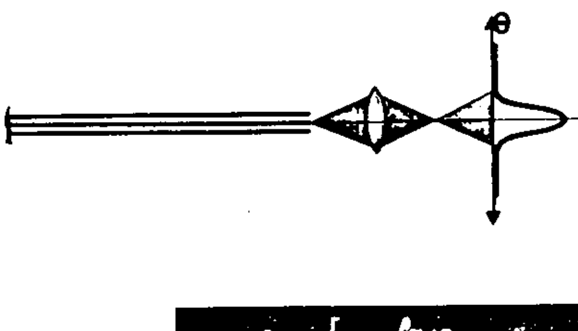
# MODE FIELD DIAMETER
## DEFINITION: $d_f$



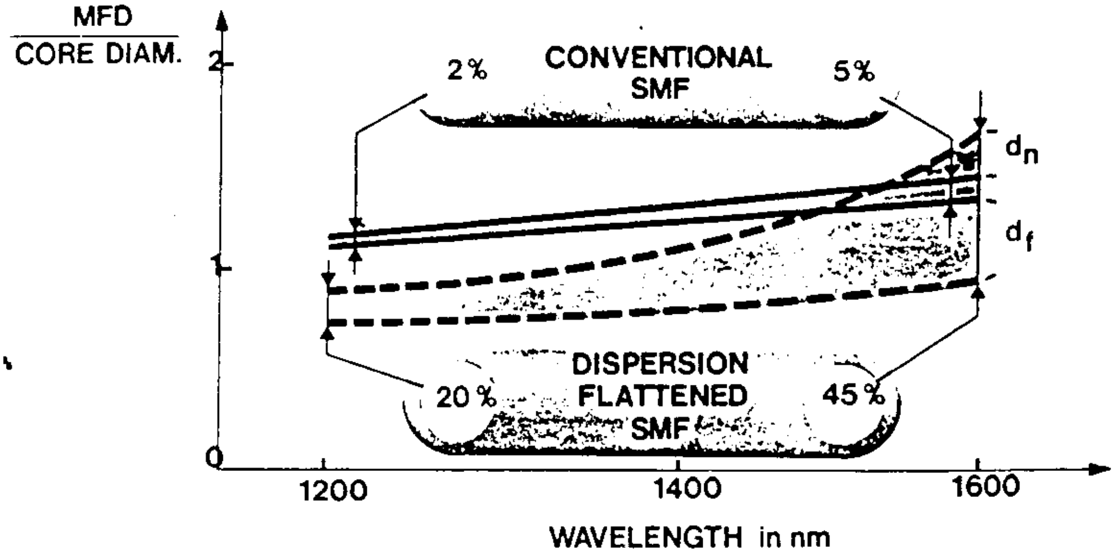

FAR-FIELD INTENSITY : $F^2(\theta)$
(FFI)

$$d_f = \frac{\lambda}{\pi}\cdot\left[2\int_0^{\pi/2} F^2\,\theta\,d\theta \Big/ \int_0^{\pi/2} \theta^2\cdot F^2\,\theta\,d\theta\right]^{1/2}$$

- $\propto$ 1/rms WIDTH OF FFI
- JOINT LOSSES FOR TRASVERSE OFFSET $\propto 1/d_f^2$
- WAVEGUIDE DISPERSION $\propto \frac{d(\lambda/d_f^2)}{d\lambda}$

# MODE FIELD DIAMETER (MFD)
## DIFFERENCE BETWEEN $d_n$ AND $d_f$

$d_n \geq d_f$ $\qquad$ $d_n = d_f$ FOR GAUSSIAN NFI (AND FFI) ONLY




- FOR CONVENTIONAL SMF (~1300 nm) : $d_n = d_f$
- FOR DISPERSION FLATTENED AND DISPERSION SHIFTED SMF : $d_n \gg d_f$

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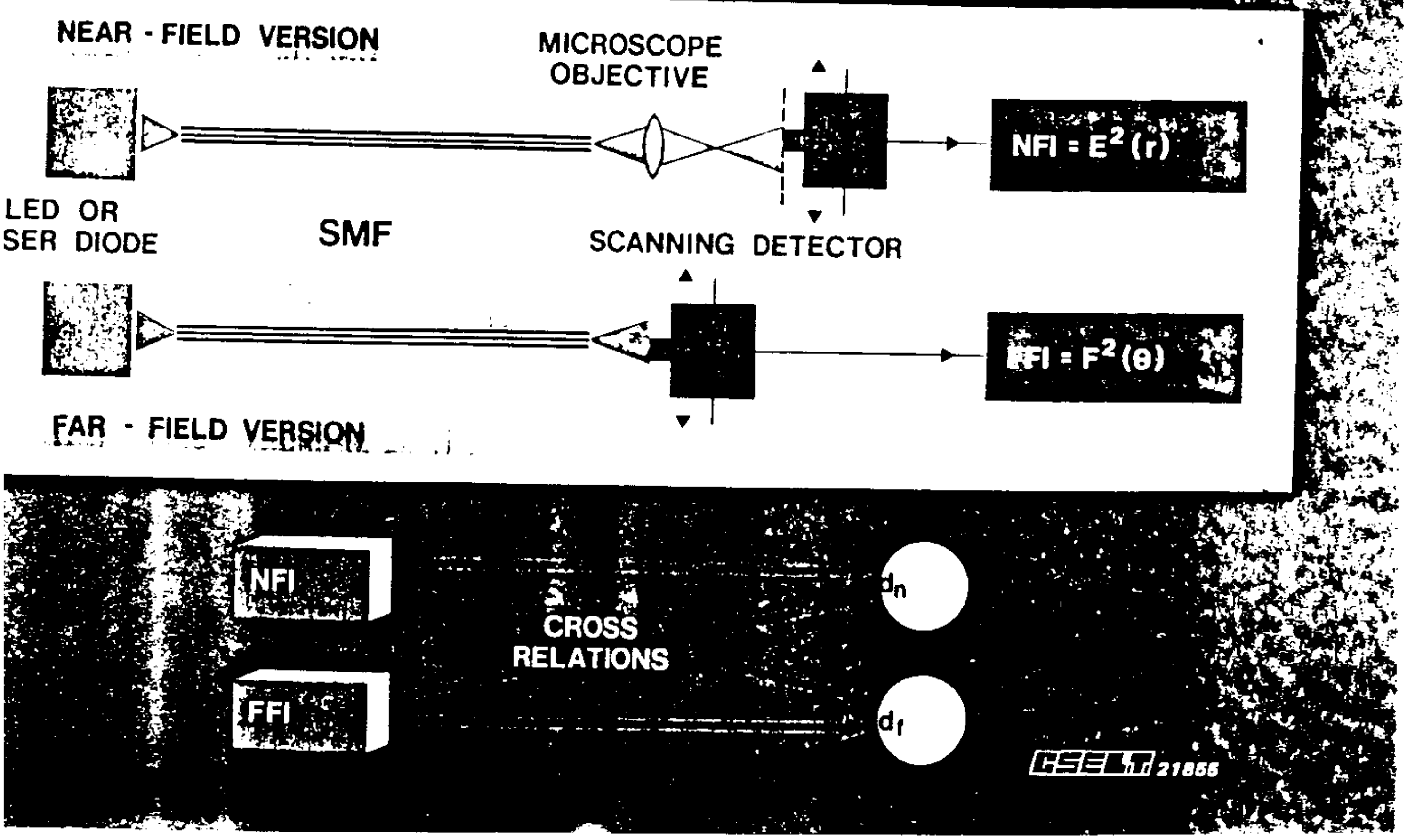
# MFD MEASUREMENTS
## TRANSMITTED FIELD TECHNIQUE

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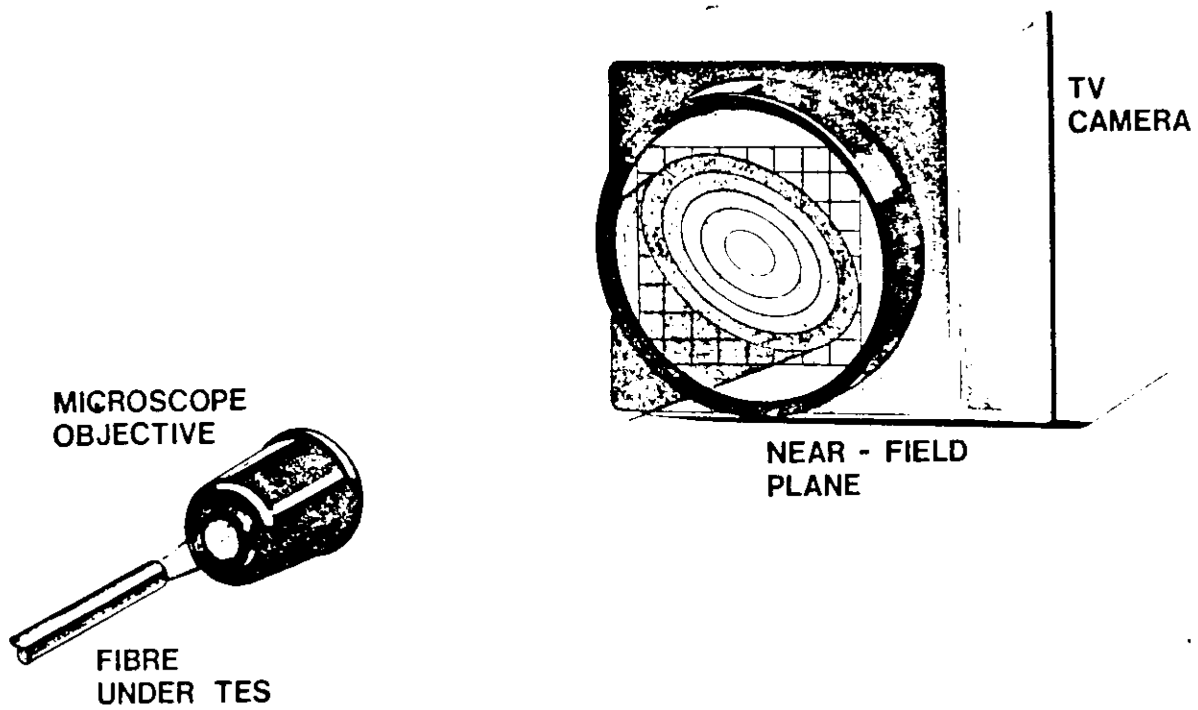
# TNF MEASUREMENT

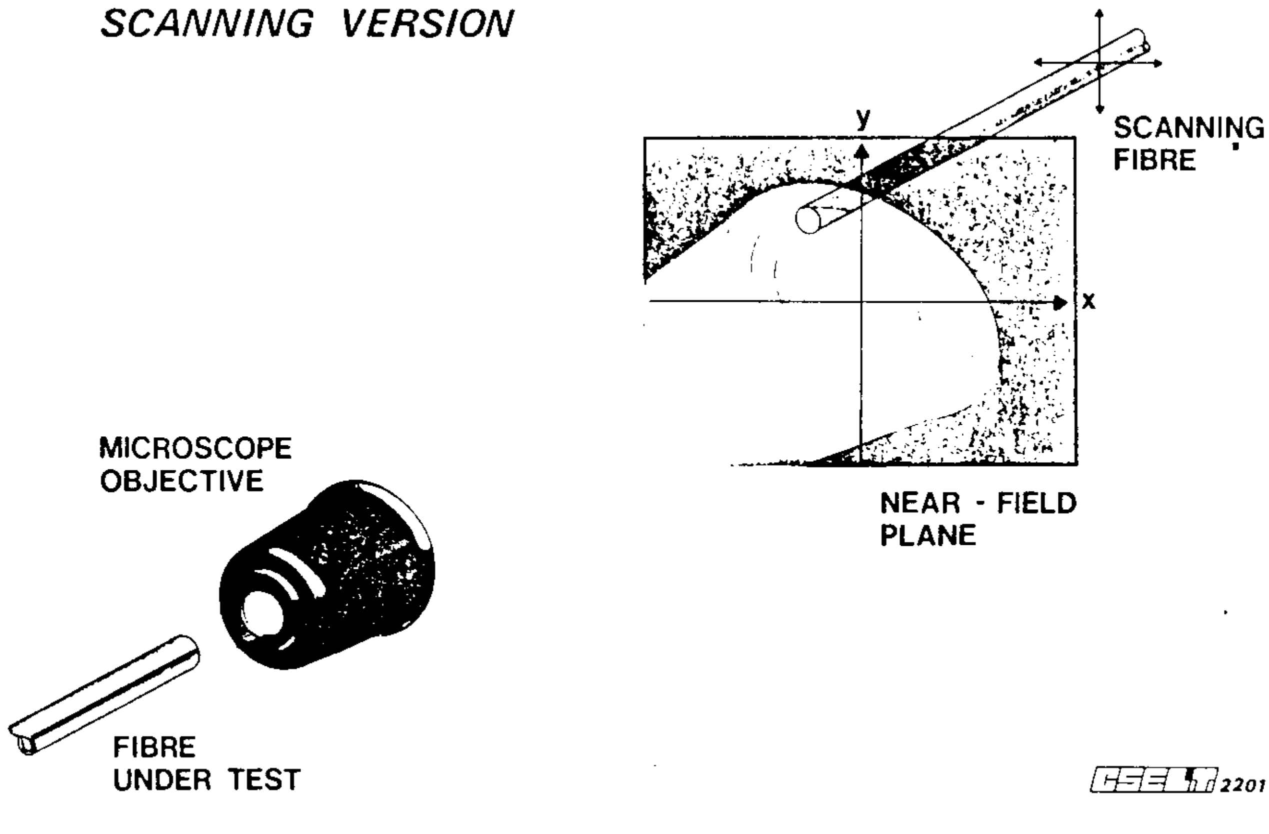
*TV CAMERA VERSION*




CSELT 22276

# TNF MEASUREMENT

*SCANNING VERSION*

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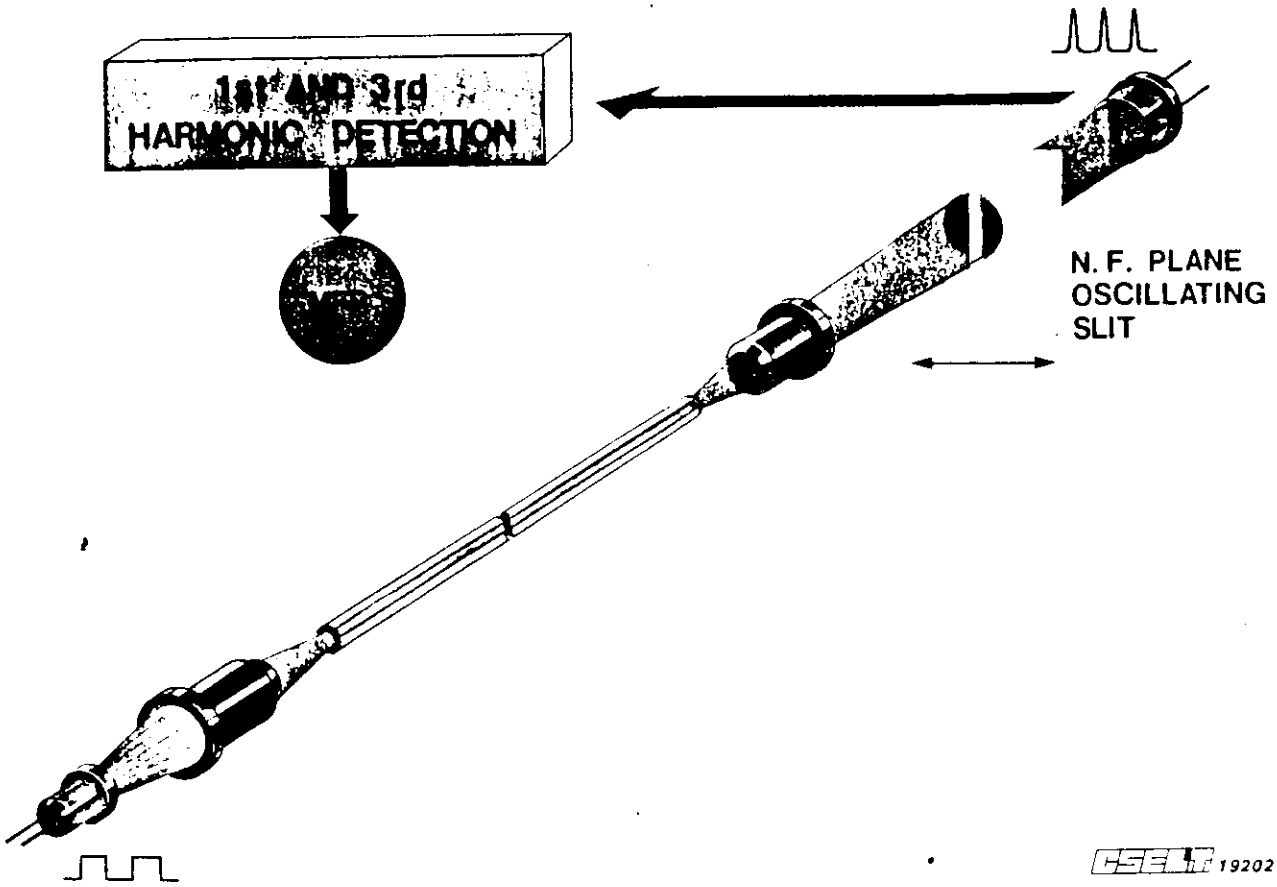


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# MFD MEASUREMENTS

- NFI and FFI scanning detection techniques:
  - Scanning small area detector
  - Scanning pig-tail, pinhole
  - Variable aperture
  - Scanning knife-edge
  - Axially scanning aperture
  - Scanning mirror
  - Scanning slit
  - Electronic scanning (vidicon, CCD,...)
- High SNR required in NFI or FFI measurements
  - Error on $d_n$ or $d_f$ < 2% for SNR > 30 dB

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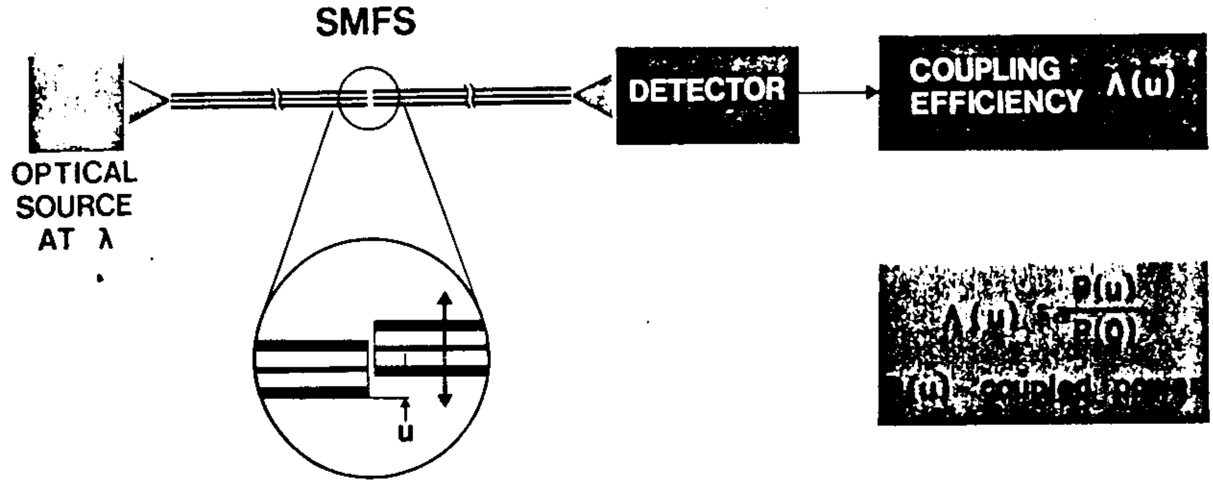
# MFD MEASUREMENTS
## TRANSVERSE OFFSET TECHNIQUE




$$\Lambda(u) = \frac{P(u)}{P(0)}$$

$P(u)$ = coupled power

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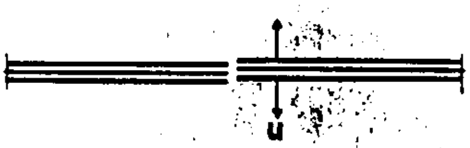
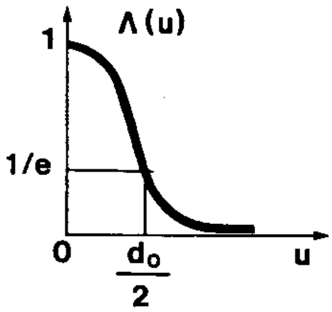
# MODE FIELD DIAMETER
## DEFINITION: $d_o$




COUPLING EFFICIENCY Λ (u)




$$d_o : \Lambda\left(\frac{d_o}{2}\right) = \frac{1}{e}$$

- $d_o \simeq d_n$ FOR CONVENTIONAL FIBRES
- ACCURATE DETERMINATION
- INDIRECT FROM NFI AND FFI

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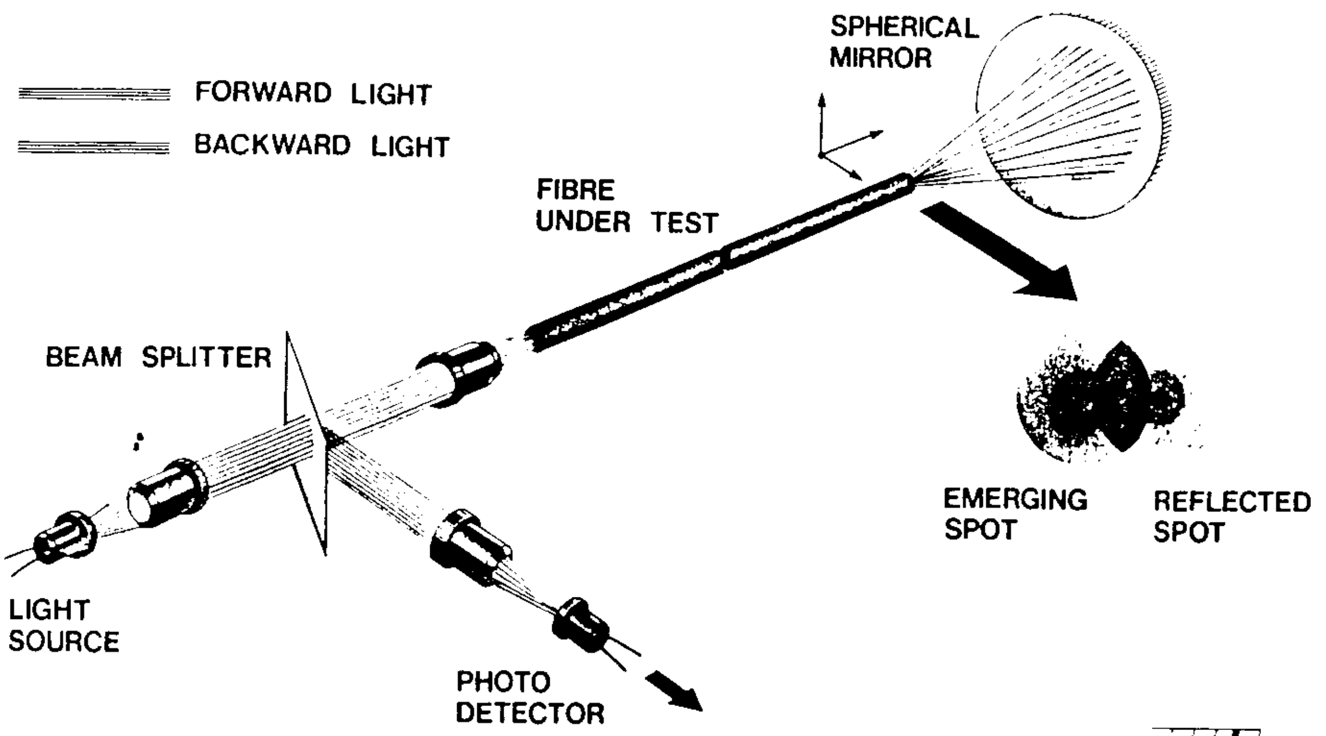
# SELF - IMAGING OFFSET MEASUREMENT

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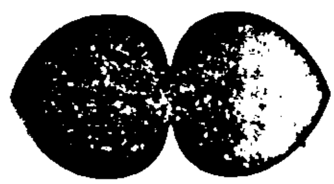
# MFD MEASUREMENTS

## THE MASK METHOD



$$\frac{d_n^2}{8} = \int_0^\infty r^2 \cdot E^2 r\,dr \Big/ \int_0^\infty E^2 r\,dr$$

$\propto P_T$ : TOTAL POWER

$\propto P_M$ : TOTAL POWER FILTERED BY A MASK WITH TRANSMITTY PROPORTIONAL TO: $r^2$

$\Rightarrow$ $d_n = D\sqrt{2 P_M / P_T}$ (D - Mask diameter)

- TWO MEASUREMENTS ($P_T$ AND $P_M$) ONLY
- ACCURATED
- SIMPLE

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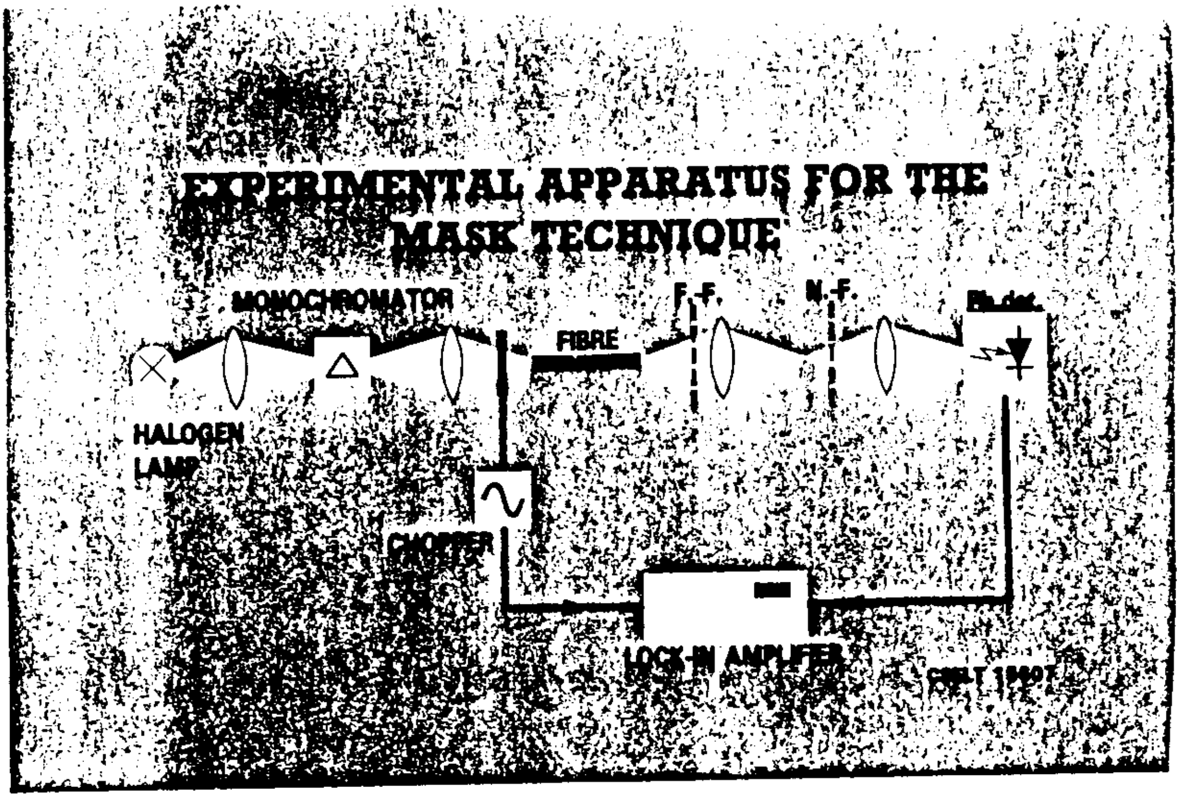


# MODE FIELD DIAMETER

## STANDARDIZATION

- DEFINITION, RTM AND ATM UNDER CONSIDERATION:

| DEFINITION | RTM | ATM |
|---|---|---|
| $d_g$ | TRANSMITTED FIELD | TRANSVERSE OFFSET |
| $d_o$ | TRANSVERSE OFFSET | TRANSMITTED FIELD |
| $d_f$ | TRANSMITTED FIELD<br>TRANSVERSE OFFSET | — — — |

# MODE FIELD DIAMETER

## STANDARDIZATION

- NOMINAL VALUE (AT 1300 nm):

  9 $\mu$m (TYPICAL OF DEPRESSED CLADDING SMFs)

  to

  10 $\mu$m (TYPICAL OF MATCHED CLADDING SMFs)

- TOLERANCE FIELD:

  MISMATCH SPLICE LOSS:

  ±10% → <0.17 dB
  <0.05 dB in 90% of cases

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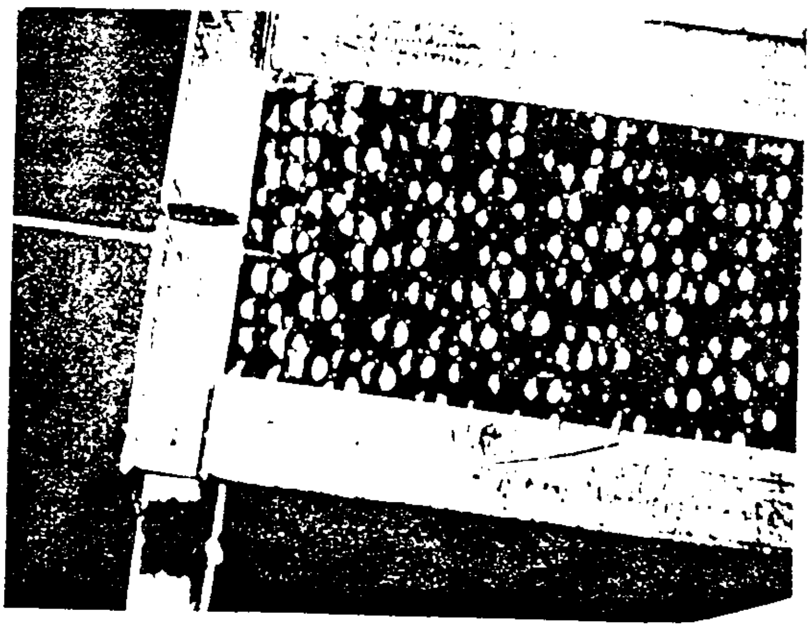
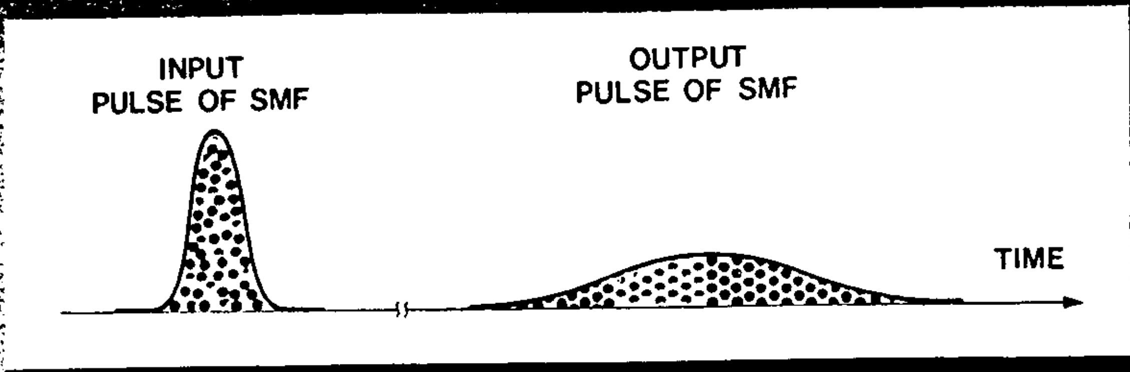


# CHROMATIC DISPERSION




- ONLY CAUSE OF PULSE BROADENING IN CONVENTIONAL SMFs
- DUE TO THE WAVELENGTH DEPENDENCE OF UNITARY GROUP DELAY : $\tau = \tau(\lambda)$
- MATERIAL AND WAVEGUIDE CONTRIBUTIONS

DEFINITION : $D(\lambda) = \dfrac{d\,\tau(\lambda)}{d(\lambda)}$

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# CHROMATIC DISPERSION

- Pulse broadening:

$$\Delta t \simeq D \cdot L \cdot \Delta\lambda$$

L - Fibre length

$\Delta\lambda$ - Spectral width of the optical source

- Units of D: ps $(\Delta t)$/[nm$(\Delta\lambda)\cdot$km (L)]
- Pulse broadening and bandwidth determined through D (their direct determination is impractical)

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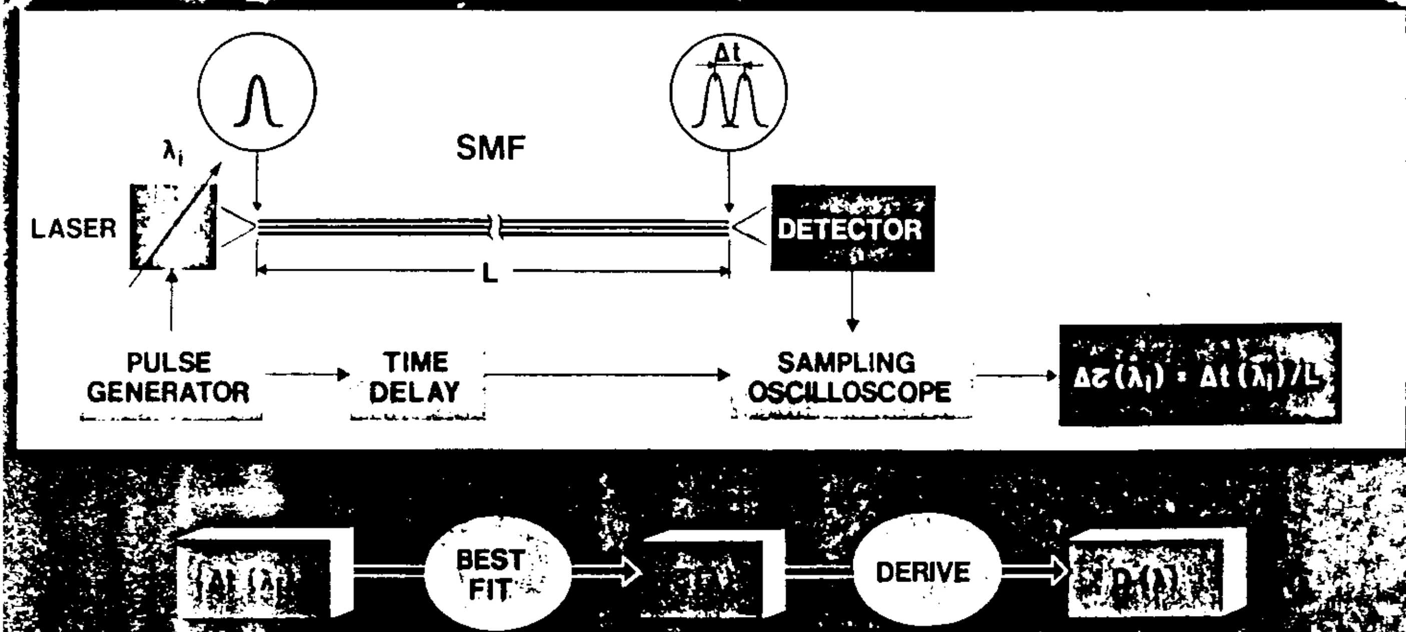
# CHROMATIC DISPERSION MEASUREMENTS
## PULSE DELAY TECHNIQUE




- RTM
- TIME DOMAIN MEASUREMENT
- MULTI WAVELENGTH PULSED LASER : { - RAMAN LASER (CUMBERSOME AND EXPENSIVE) - MULTIPLE LASER DIODES (FEW λ POINTS)

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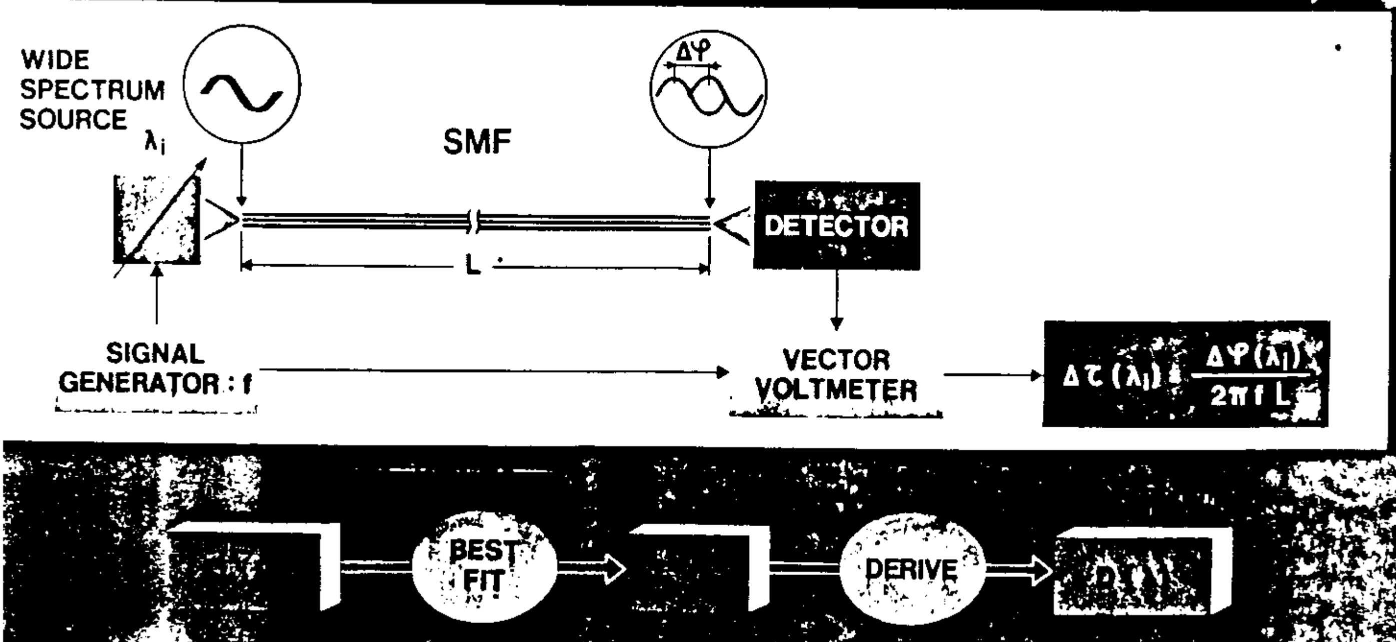
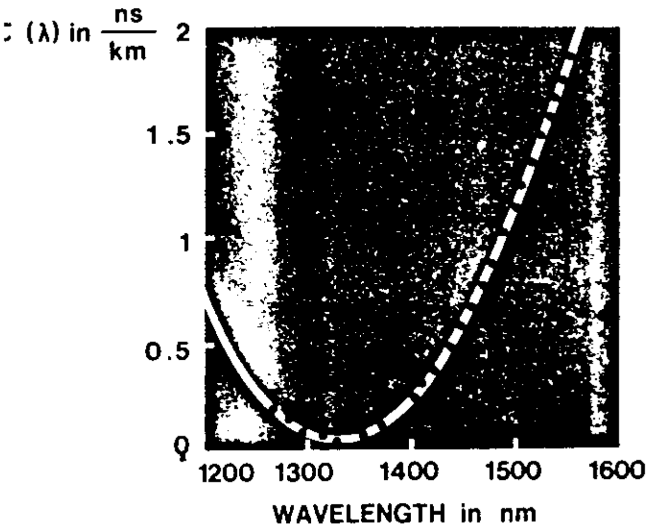
# CHROMATIC DISPERSION MEASUREMENTS
## PHASE SHIFT TECHNIQUE

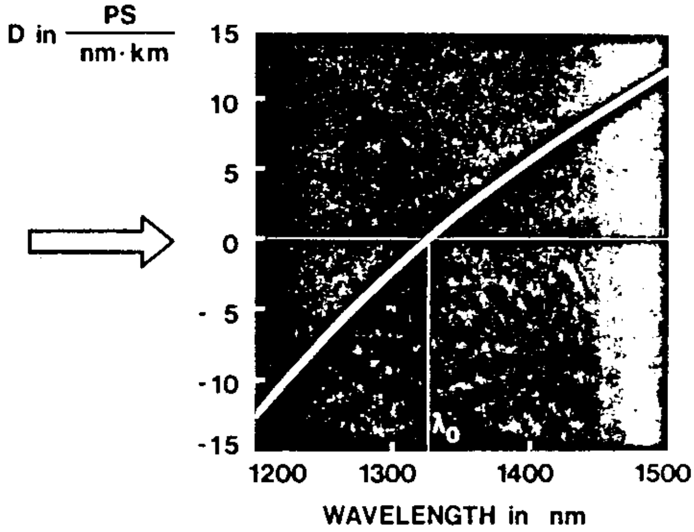



- RTM
- FREQUENCY DOMAIN MEASUREMENT
- BASE FOR PRATICAL INSTRUMENTS
- WIDE SPECTRUM LIGHT SOURCE : { - LEDS (LIMITED DYNAMICS) - MULTIPLE LASER DIODES (FEW λ POINTS)

# CHROMATIC DISPERSION MEASUREMENT

## FITTING EQUATION




FOR CONVENTIONAL FIBRES ( 3 – TERMS SELLMEIER EQUATION )

$$\tau(\lambda) = \tau_0 + \frac{S_0}{8}\left(\lambda - \frac{\lambda_0^2}{\lambda}\right)^2 \Rightarrow D(\lambda) = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right)$$

- $\lambda_0$ : ZERO DISPERSION WAVELENGTH
- $\tau_0$ : $\tau$ AT $\lambda_0$
- $S_0$ : SLOPE $d D/d\lambda$ AT $\lambda_0$

FOR DISPERSION SHIFTED OR DISPERSION FLATTENED FIBRES DIFFERENT FITTING EQUATIONS MAY BE NEEDED

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# CHROMATIC DISPERSION

## *SHORT LENGTH TECHNIQUES*

- Interferometry
  - \+ Resolution: 0.1 ps
  - \- Interferometric set-up
- MFD vs. $\lambda$
  - \+ Waveguide dispersion
  - \- Material dispersion needed

— Extrapolation to full lengths?

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# CHROMATIC DISPERSION

## STANDARDIZATION

| Maximum D value | Operation wavelengths |
|---|---|
| 3.5 ps/(nm•km) | 1285-1330 nm |
| 6 ps/(nm•km) | 1270-1340 nm |
| 20 ps/(nm•km) | 1550 nm |

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# REFRACTIVE INDEX PROFILE

- *NOT STANDARDIZED FOR SMF*
  ($\lambda_c$, MFD and D sufficient)
- *MEASUREMENT TECHNIQUES*
  - PREFORM
    - Elaboration of deviation of light refracted laterally
  - FIBRE
    - Refracted near-field
    - Transmitted near-field (inverting the wave equation)

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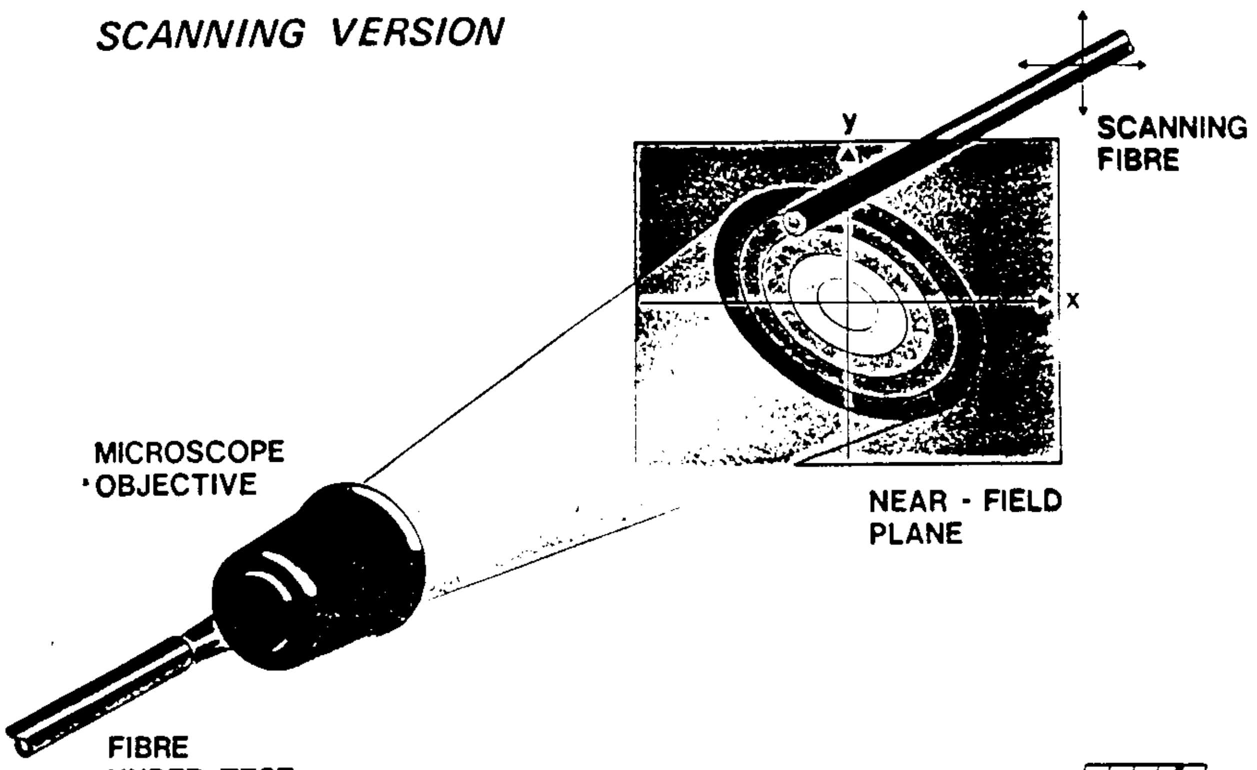
# TNF MEASUREMENT

*SCANNING VERSION*

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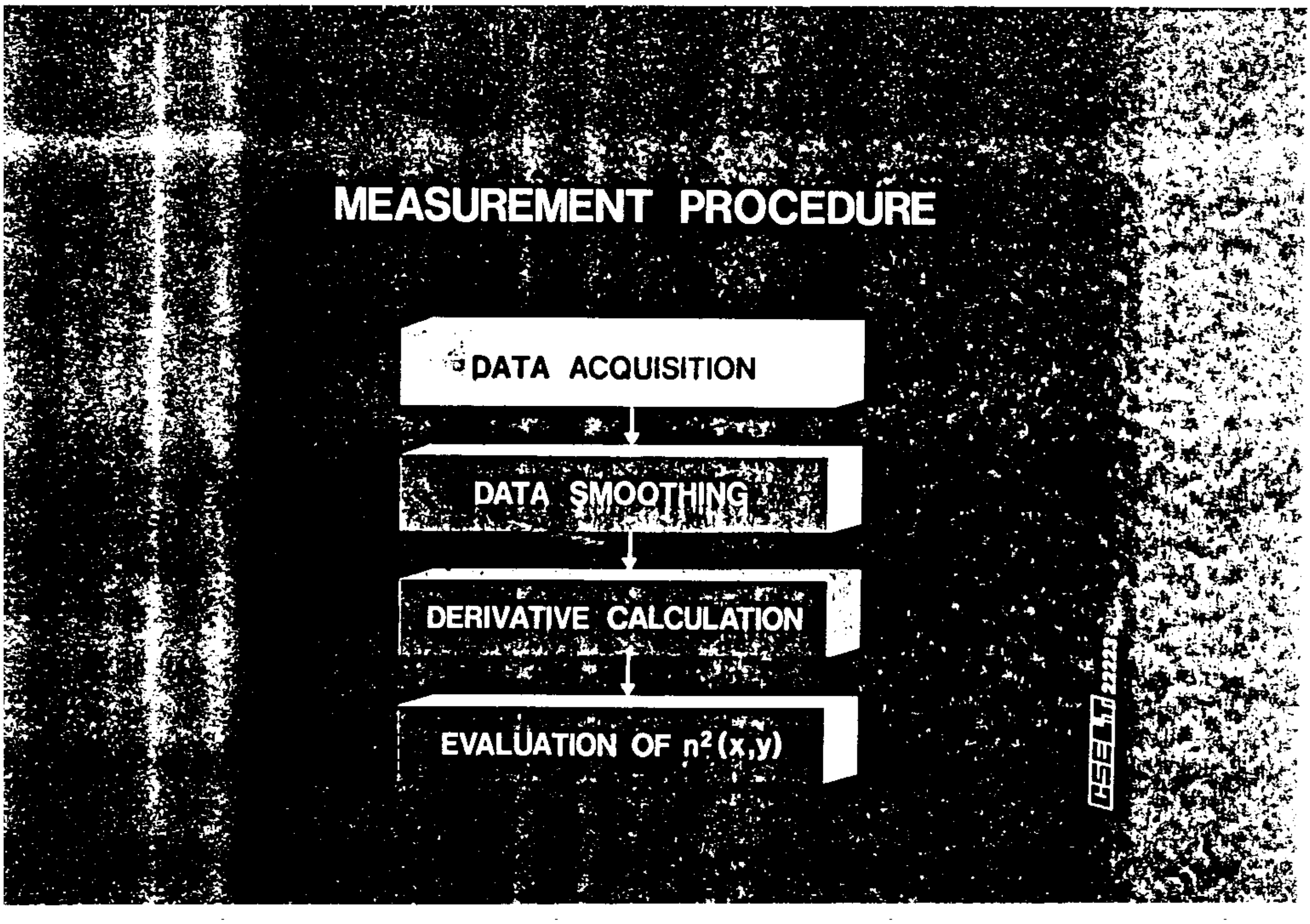

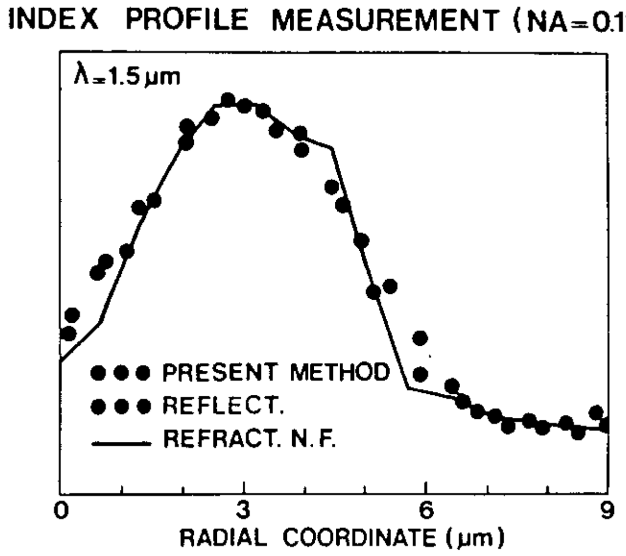


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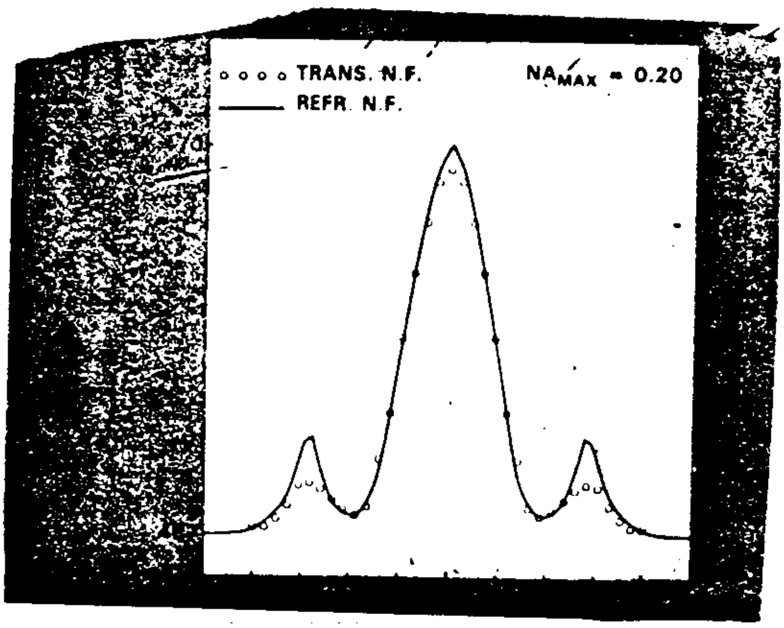
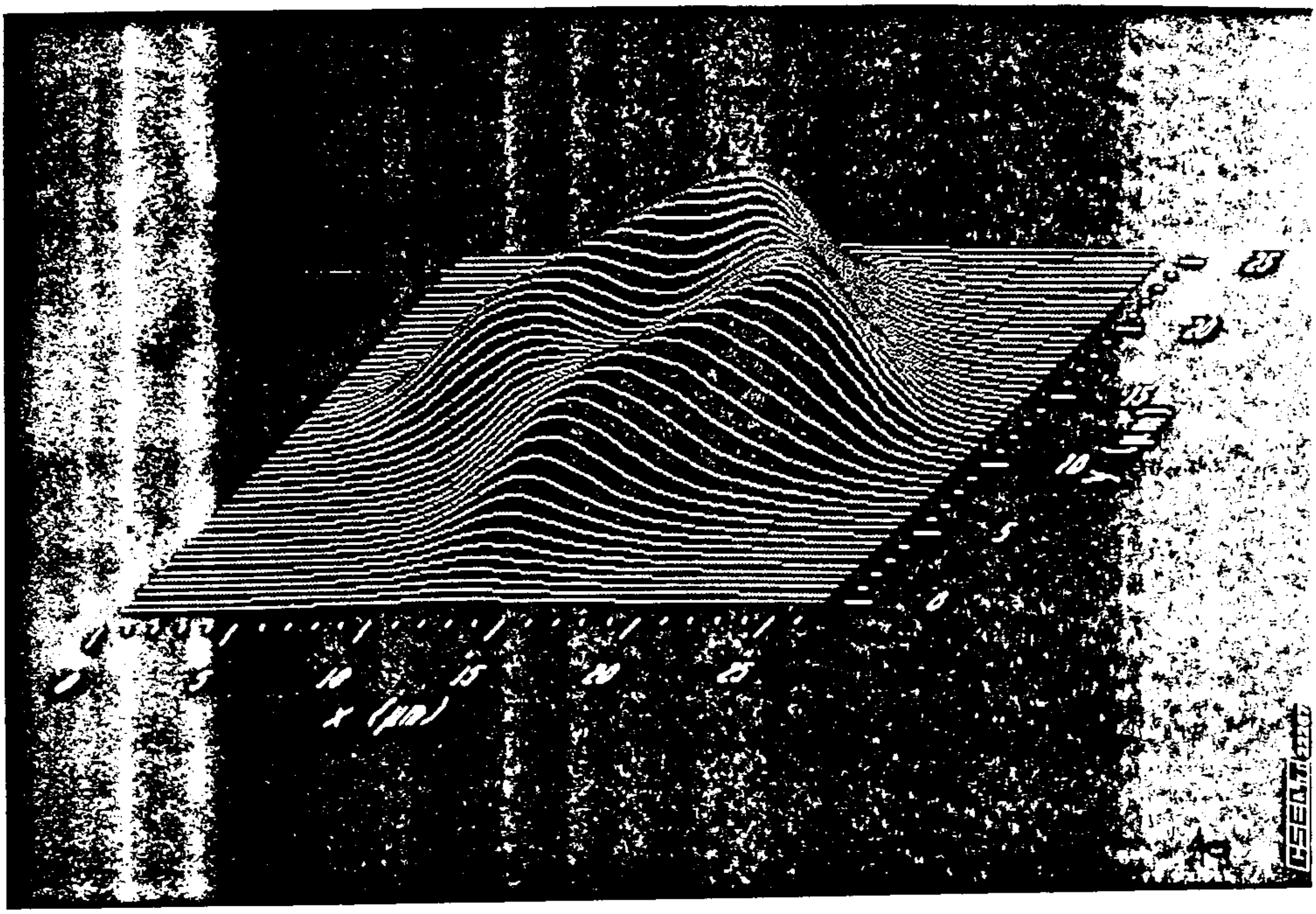
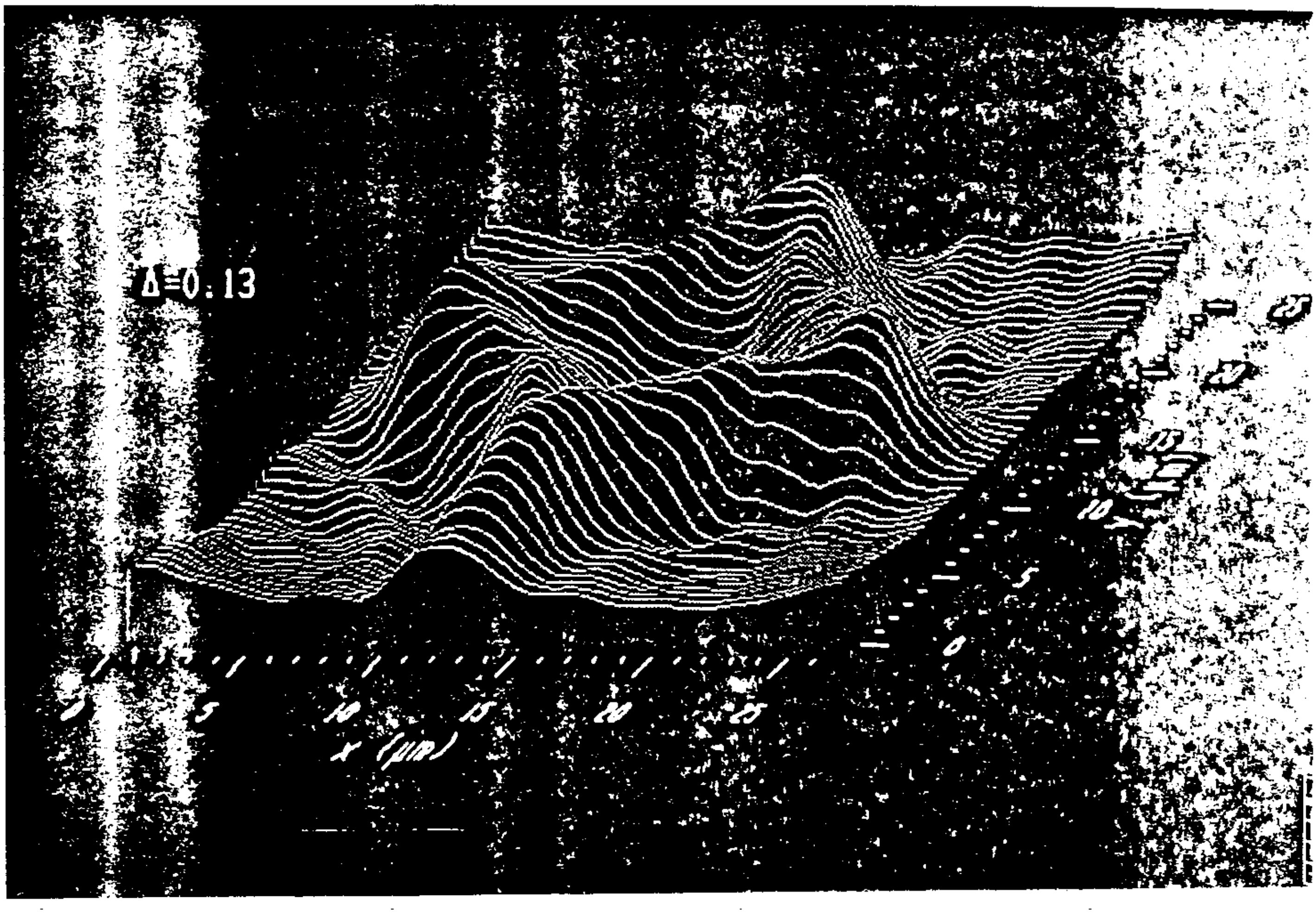



x (μm)
y (μm)
0
5
10
15
20
25
CSELT


Δ=0.13
x (μm)
y (μm)
0
5
10
15
20
25

# SMF GEOMETRY

## STANDARDIZATION

| Parameter | Nominal Value | Tolerance Field |
|---|---|---|
| CLADDING DIAMETER | 125 $\mu m$ | $\pm 2,4\%$ |
| MODE FIELD DIAMETER | 9-10 $\mu m$ | $\pm 10\%$ |
| CLADDING NON-CIRCULARITY | — | 2% |
| MODE FIELD NON-CIRCULARITY | — | (6%) |
| CLADDING-MODE FIELD CONCENTRICITY ERROR | — | $1 \mu m (3 \mu m)$ |

## MEASUREMENT TECHNIQUE

BY VIDEO SYSTEMS WITH DIGITIZING FACILITIES AND SUITABLE SOFTWARE FOR CLADDING AND MODE FIELD AREAS

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# POLARIZATION PROPERTIES MEASUREMENTS

- Polarization cross-talk
- Output degree of polarization
- Output state of polarization
- Beat length
- Dichroism

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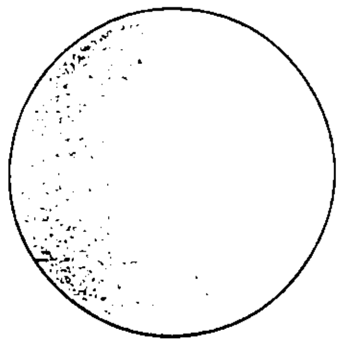
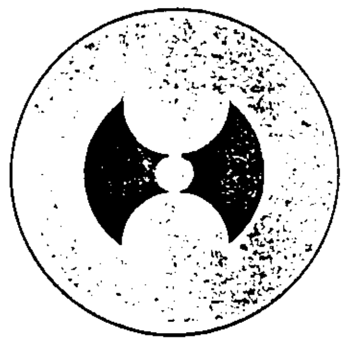
# SINGLE - MODE FIBRES



CONVENTIONAL



POLARIZATION MAINTAINING

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# MECHANICAL TESTS

- Tensile strength (on fibre, jacket and cable)
- Temperature-bending
- Impact resistance
- Compressive strength
- Torsion
- Flexure
- Hermeticity

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# CONCLUSION

- **SMF Technology still under evolution**
  - New fibre design
  - New system phylosophies

- **Industrial characterization already mature**
  - Standardization substantially established
  - Practical and accurate instruments available

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