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INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

(5 February - 2 March 1990)

ATTENUATION MEASUREMENTS

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ATTENUATION MEASUREMENTS

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ATTENUATION

THE ATTENUATION OF OPTICAL POWER IN A SILICA FIBER IS CAUSED BY THESE THREE EFFECTS:

- MATERIAL ABSORPTION → INTRINSIC ABS. / → EXTRINSIC "
- RAYLEIGH SCATTERING
- BENDING

THE ATTENUATION CAUSES AN EXPONENTIAL DECAY OF THE OPTICAL POWER ALONG THE FIBER:

$$P(z) = P_0 \exp(-\alpha' z)$$

$P(z)$ = OPT. POWER AT A DISTANCE z FROM INPUT

P_0 = OPT. POWER AT FIBER INPUT

α' = ATTENUATION COEFFICIENT (1/Km)

THE ATTENUATION IS USUALLY EXPRESSED IN dB:

$$P(z) = P_0 \cdot 10^{-\alpha z / 10\,dB}$$

$$\log_{10} P(z) = \alpha z / 10\,dB + \log_{10} P_0 \quad [dB\ opt]$$

WHERE:

$$\alpha = \frac{1}{z} \log_{10} \frac{P_0}{P(z)} \quad (dB/Km)$$

IS THE ATTENUATION COEFFICIENT IN dB/Km

$$\alpha = \alpha_{SCATT.} + \alpha_{ABS.} + \alpha_{BEND.}$$

- Material Absorption Losses.

- INTRINSIC ABSORPTION:

IT IS CAUSED BY THE INTERACTION WITH ONE OR MORE OF THE MAJOR COMPONENTS OF THE GLASS.

ULTRAVIOLET ABS. : IT IS DUE TO THE STIMULATION OF ELECTRON TRANSITIONS WITHIN THE GLASS. THE TAIL OF THIS PEAK MAY EXTEND INTO THE WINDOW AT SHORTEST WAVELENGTHS.

INFRARED AND FAR INFRARED ABS. : IT IS DUE TO THE INTERACTIONS OF PHOTONS WITH MOLECULAR VIBRATIONS WITHIN THE GLASS. THESE GIVE ABSORPTION PEAKS WHICH AGAIN EXTEND INTO THE WINDOW REGION. ABOVE 1.5 μm THE TAIL OF THOSE LARGELY FAR INFRARED ABSORPTION PEAKS TEND TO CAUSE MOST OF THE GLASS LOSSES.

- EXTRINSIC ABSORPTION:

IT IS CAUSED BY IMPURITIES WITHIN THE GLASS.

- FROM THE TRANSITION METALLIC ELEMENT IMPURITIES INTO THE GLASS. TRANSITION ELEMENT CONTAMINATIONS MAY BE REDUCED WITH THE VAPOR PHASE DEPOSITION TECHNIQUE.

ABSORPTION DUE TO THE WATER (AS THE OH IONS) DISSOLVED IN THE GLASS. THESE OH GROUPS ARE BOUNDED INTO THE GLASS STRUCTURE AND HAVE FUNDAMENTAL VIBRATIONS AT 2.7 AND 4.2 μm.
THE FUNDAMENTAL VIBRATIONS GIVE RISE TO OVERTONES APPEARING AT 1.38; 0.95; 0.72 μm
FURTHERMORE COMBINATIONS BETWEEN THE OVERTONES AND SiO_2 VIBRATION OCCOUR AT 1.24; 1.13; 0.88 μm.

LINEAR SCATTERING (RAYLEIGH SCATT.)

IT IS THE DOMINANT INTRINSIC LOSS MECHANISM IN THE LOW ABSORPTION WINDOW. IT IS DUE FROM INHOMOGENEITIES ARISING FROM DENSITY AND COMPOSITIONAL VARIATIONS INTO THE GLASS. THESE INHOMOGENEITIES MANIFEST THEMSELVES AS REFRACTIVE INDEX FLUCTUATIONS. THE COMPOSITIONAL VARIATIONS MAY BE REDUCED BUT THE INDEX FLUCTUATIONS CANNOT BE AVOIDED.

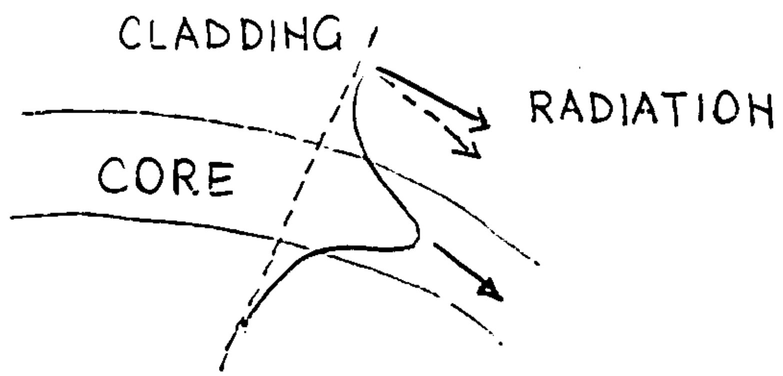
THE RAYLEIGH SCATTERING COEFFICIENT:

$$\gamma \propto \frac{1}{\lambda^4}$$

IT IS STRONGLY REDUCED BY OPERATING AT THE LONGEST WAVELENGTHS.

FIBER BEND LOSS

OPT. FIBERS SUFFER RADIATION LOSSES AT BENDS OR CURVES ON THEIR PATHS

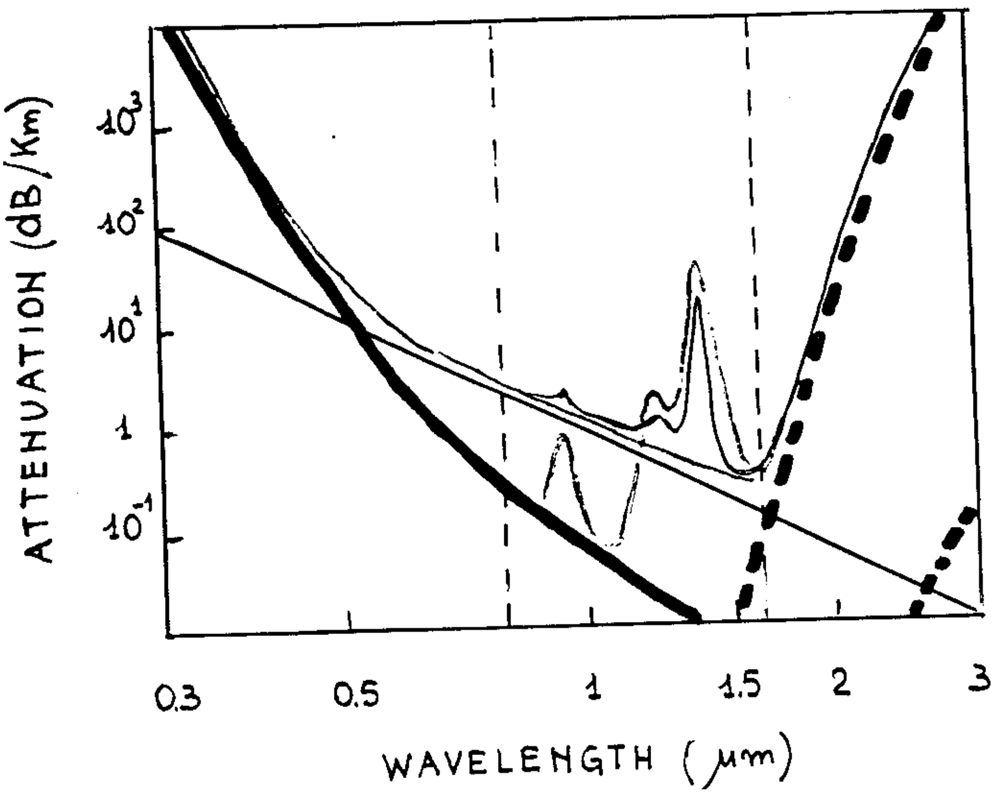


THE PART OF THE MODE IN THE CLADDING OUTSIDE THE DASHED ARROWED LINE MAY BE REQUIRED TO TRAVEL FASTER THAN THE VELOCITY OF THE LIGHT IN ORDER TO MAINTAIN A PLANE WAVEFRONT. SINCE IT CANNOT DO THIS, THE ENERGY IN THIS PART OF MODE IS RADIATED.

BENDING LOSSES MAY BE REDUCED:

- DESIGNING FIBERS WITH LARGE REFR. INDEX DIFFERENCIES
- OPERATING AT SHORTEST WAVELENGTH POSSIBLE.

FINALLY IT IS IMPORTANT THAT MICROSCOPIC BENDS (MICROBENDS) WITH RADII OF CURVATURE APPROXIMATING TO THE FIBER RADIUS ARE NOT PRODUCED IN THE FIBER CABLING PROCESS BECAUSE THEY CAN CAUSE SIGNIFICANT LOSS INCREASES.



ULTRAVIOLET ABSORPTION

INFRARED "

RAYLEIGH SCATTERING

ABSORPTION SPECTRUM OF OH

TOTAL INTRINSIC ATTENUATION

ATTENUATION MEASURED ON A TYPICAL SINGLE MODE FIBER.

ATTENUATION MEASUREMENTS.

THREE METHODS ARE COMMONLY USED TO PERFORM ATTENUATION MEASUREMENTS:

- CUT-BACK METHOD
- INSERTION-LOSS "
- BACKSCATTERING "

- CUT-BACK METHOD:

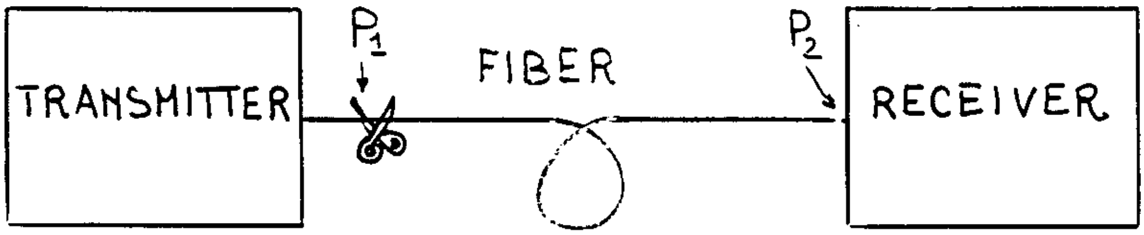
THE CUT-BACK METHOD IS THE MOST ACCURATE AND IT IS THE REFERENCE METHOD.

AFTER MEASURING THE POWER AT THE FAR END, THE FIBER IS CUT NEAR THE INPUT END WITHOUT CHANGING THE LAUNCHING CONDITIONS (THE CUT IS NORMALLY PERFORMED AFTER TWO OR THREE METERS OF FIBER).

THE ATTENUATION CAN BE MEASURED AT A SINGLE WAVELENGTH OR AT SEVERAL WAVELENGTHS (OBTAINING THE SPECTRAL ATTENUATION OF A FIBER).

THE ONLY PROBLEM OF THIS METHOD IS ITS DESTRUCTIVE NATURE.

CUT-BACK METHOD



$$A(dB) = 10 \cdot \log \frac{P_1}{P_2}$$

$$\alpha(dB/Km) = \frac{1}{L} \cdot A = \frac{1}{L} 10 \log \frac{P_1}{P_2}$$

L = LENGTH OF FIBER UNDER TEST.

INSERTION-LOSS METHOD

THE CUT-BACK METHOD HAS THE MAJOR DRAWBACK OF BEING A DESTRUCTIVE METHOD. IT IS USEFUL IN THE LABORATORY OR IN THE FIBERS OR CABLES FACTORY BUT IT IS NOT APPLIABLE IN THE FIELD.

THE INSERTION-LOSS METHOD PERMITS TO MEASURE THE FIBER ATTENUATION THROUGH A SINGLE READING OF THE OPTICAL POWER AT THE FAR END OF THE FIBER AFTER

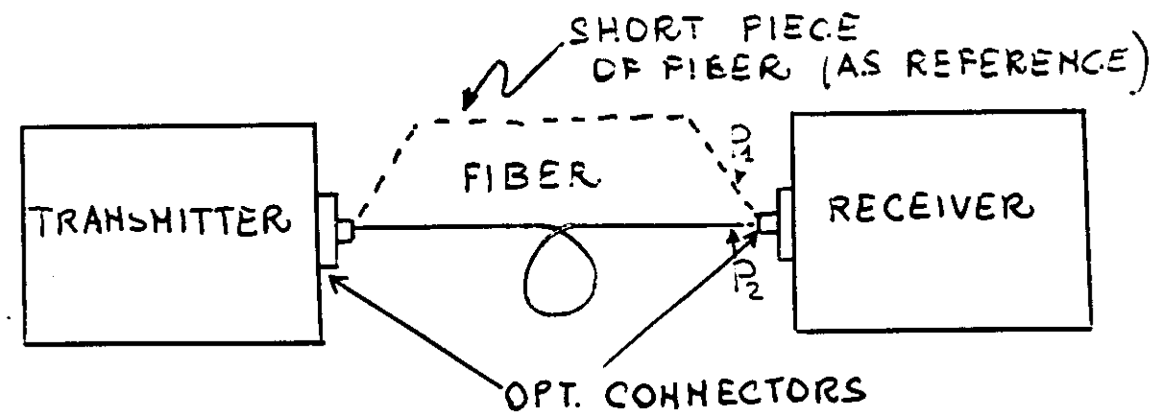
DETERMINATION OF THE NEAR END POWER LEVEL.

THE FIBER IS GENERALLY CONNECTED AT THE TRANSMITTER AND THE RECEIVER BY MEANS OF CONNECTORS.

THE MEASUREMENT IS CARRIED OUT IN A SIMILAR MANNER TO THE CUT-BACK METHOD BUT ITS ACCURACY IS DEPENDENT ON THE COUPLING BETWEEN THE TRANSMITTER AND THE FIBER AND IS GENERALLY SOMEWHAT UNCERTAIN.

THE COUPLING IN THE RECEIVER IS ALSO CRITICAL BUT LESS THAN IN THE TRANSMITTER IF A LARGE AREA DETECTOR IS USED.

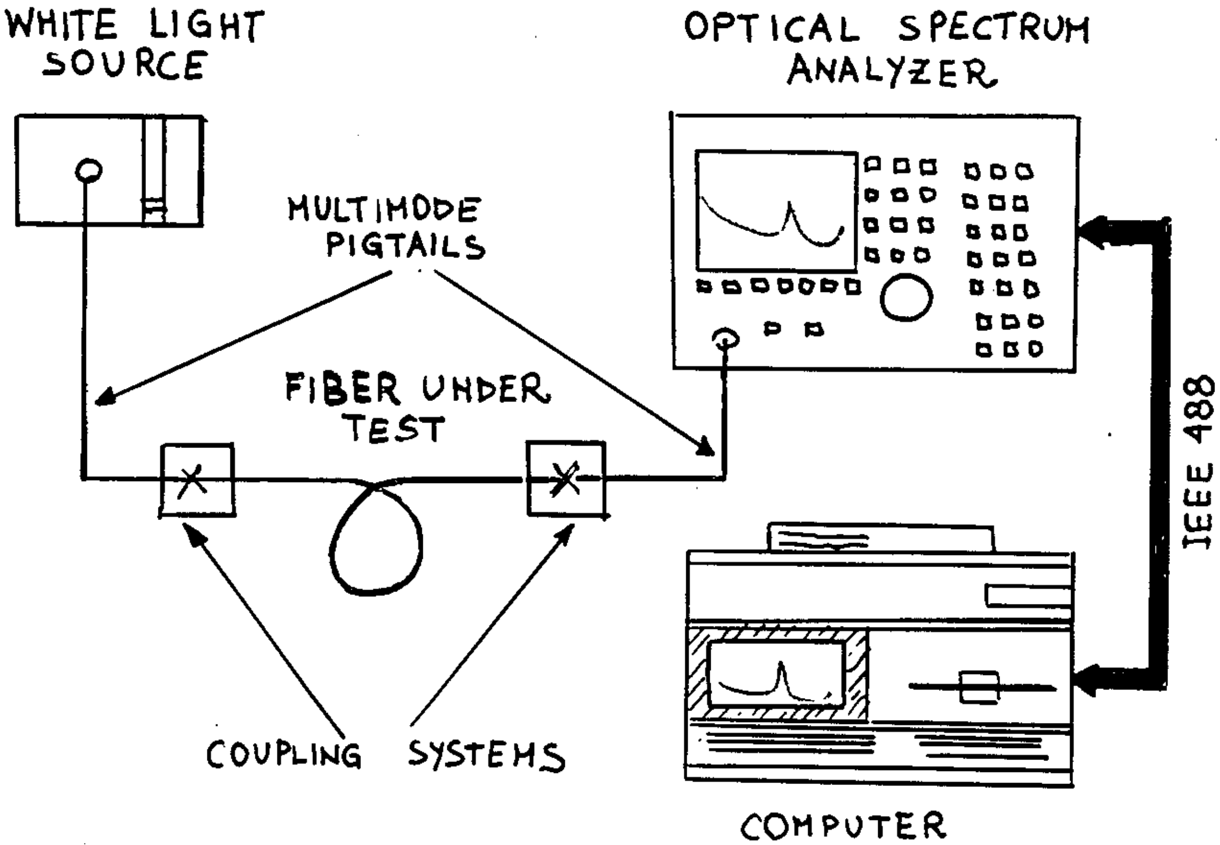
INSERTION-LOSS METHOD



$$A(dB) = 10 \log \frac{P_1}{P_2}$$

SPECTRAL ATTENUATION MEASURING SET-UP
- CUT-BACK METHOD -

- A LARGE SPECTRUM SOURCE IS USED TO PERFORM SPECTRAL MEASUREMENTS (A TUNGSTEN HALOGEN LAMP).
- A MONOCHROMATOR PERMITS THE SELECTION OF λ (WITH A DEFINED SPECTRAL RESOLUTION $\Delta\lambda$ ($5 \div 10$ mm).
  A MONOCHROMATOR IS A WAVELENGTH-TUNABLE OPTICAL FILTER, BASED ON A DIFFRACTION GRATING. THE GRATING SEPARES DIFFERENT λ SPATIALLY. AN APERTURE SELECTS WHICH WAVELENGTHS ARE PASSED THROUGH THE DETECTOR. TUNING IS PERFORMED BY ROTATING THE GRATING. THE SPECTRAL RESOLUTION $\Delta\lambda$ IS DEFINED BY THE APERTURE SIZE.
- THE OPT. POWER AT THE RECEIVING END IS DETECTED BY USING A Ge OR InGaAs P.I.N PHOTODETECTOR.



TRANSMITTING UNIT:

WHITE LIGHT SOURCE: AN HALOGEN LAMP IS USED; A LENS SYSTEM PERMITS TO OBTAIN A FOCUSED LIGHT ON THE OUTPUT OPTICAL CONNECTOR. THE OUTPUT OPT. LEVEL ON A S.M. FIBER IS ABOUT -63 dBm / 5nm (500 pW).

RECEIVING UNIT:

AN OPT. SPECTRUM ANALYZER (WITH HIGH SENSITIVITY) CONTROLLED BY A COMPUTER IS USED.

- MIN. LEVEL : -75 dBm / 5nm ; RANGE OF λ : 0.6 ÷ 1.75 μm

IN BOTH THE TRANSMITTING AND IN THE RECEIVING END SHORT PIECES OF MULTIMODE STEP-INDEX FIBERS (50/125 μm) ARE USED FOR COUPLING THE SINGLE-MODE FIBER IN MEASURE TO THE MEASURING SET-UP. THE COUPLING SYSTEM IS BASED ON A MECHANICAL JOINT.

THE SPECTRAL ATTENUATION OF A S.M. FIBER CONSISTS IN:

- A MEASURE OF THE OPT. POWER LEVELS VARYING λ ON THE SPECTRUM ANALYZER AT THE OUTPUT OF THE FIBER. THE VARIOUS POWER LEVELS ARE ACQUIRED BY THE COMPUTER.

- THE FIBER IS THEN CUT-BACK NEAR THE INPUT END AND, MAINTAING, THE SAME LAUNCHING CONDITIONS, ANOTHER SET OF MEASUREMENTS (AT THE SAME λ) IS TAKEN.

- THE FIBER ATTENUATION IS CALCULATED AS THE LEVEL DIFFERENCE (IN dB, IF THE LEVELS ARE MEASURED IN dBm) AT VARIOUS λ.

INSERTION-LOSS SET-UP

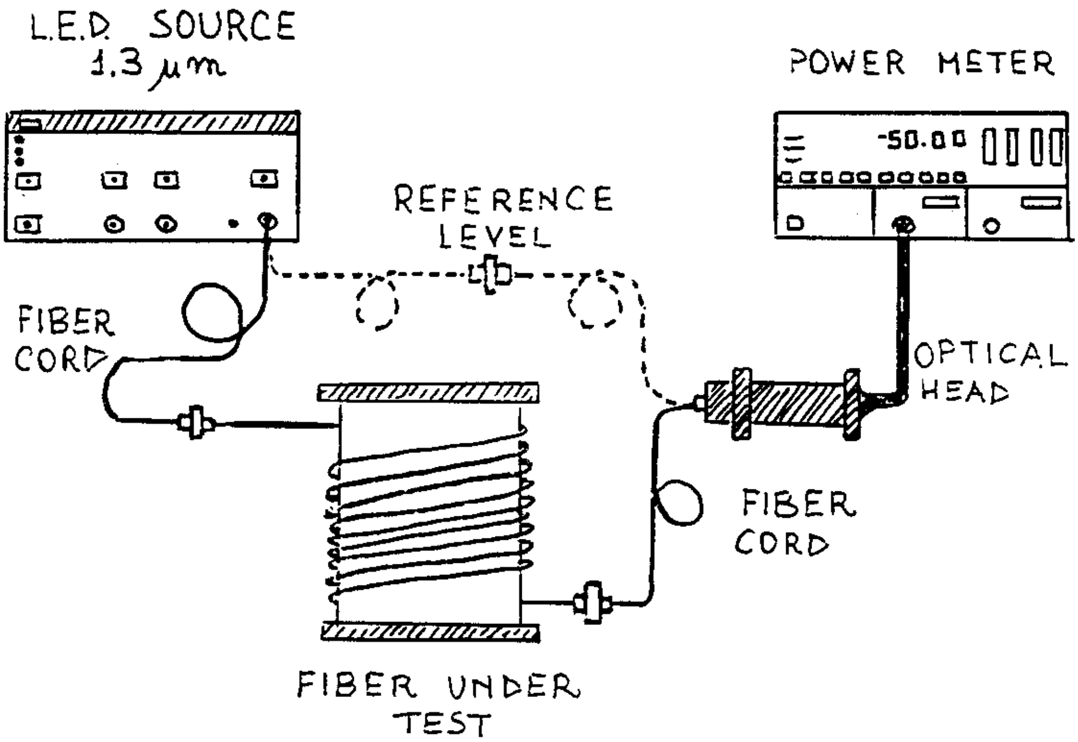
THE INSERTION-LOSS SET-UP IS NORMALLY USED FOR FIELD MEASUREMENTS ON LONG OPTICAL LINKS, GENERALLY AT A WELL DEFINED WAVELENGTH (THE WAVELENGTH OF THE TRANSMISSION SYSTEM, FOR S.M. FIBERS 1.3 AND 1.55 μm).

A L.E.D. OR A LASER DIODE (L.D.) SOURCE IS NORMALLY USED IN THE TRANSMITTING UNIT.

- WITH A L.E.D. SOURCE THE OPT. POWER COUPLED INTO A S.M. FIBER IS ABOUT -20 ÷ -30 dBm (1 ÷ 10 μW). THIS SOURCE HAS A CONTINUOUS SPECTRUM WITH A FULL WIDTH, HALF MAXIMUM (FWHM) OF 50 ÷ 70 nm (AT 1.3 μm) AND 100 nm (AT 1.55 μm).
- WITH A L.D. SOURCE THE POWER TIPICALLY COUPLED INTO A S.M. FIBER IS ABOUT 0 dBm (1 mW), THE SPECTRAL WIDTH IS OF 3 ÷ 5 nm (AT 1.3 AND 1.55 μm).

AN OPTICAL "POWER-METER" IS NORMALLY USED AS A RECEIVER. THIS DEVICE MEASURES AN ABSOLUTE OPT. POWER OVER A SPECIFIED SPECTRAL RANGE (e.g. 0.9 ÷ 1.7 μm).

IT CONSISTS OF AN OPTICAL HEAD (A SUITABLE PHOTODETECTOR) AND A METER WITH HIGH SENSITIVITY (UP TO -90 ÷ -100 dBm)



TRANSMITTER : L.E.D. SOURCE (λ = 1.3 μm , $\Delta\lambda$ = 60 nm)
POWER LEVEL INTO S.M. FIBER ~ -27 dBm

RECEIVER : POWER METER WITH OPTICAL HEAD (COOLED Ge P.I.N. DIODE).
WAVELENGTH RANGE : 0.9 ÷ 1.7 μm
MEASUREMENT RANGE : +3 ÷ -80 dBm

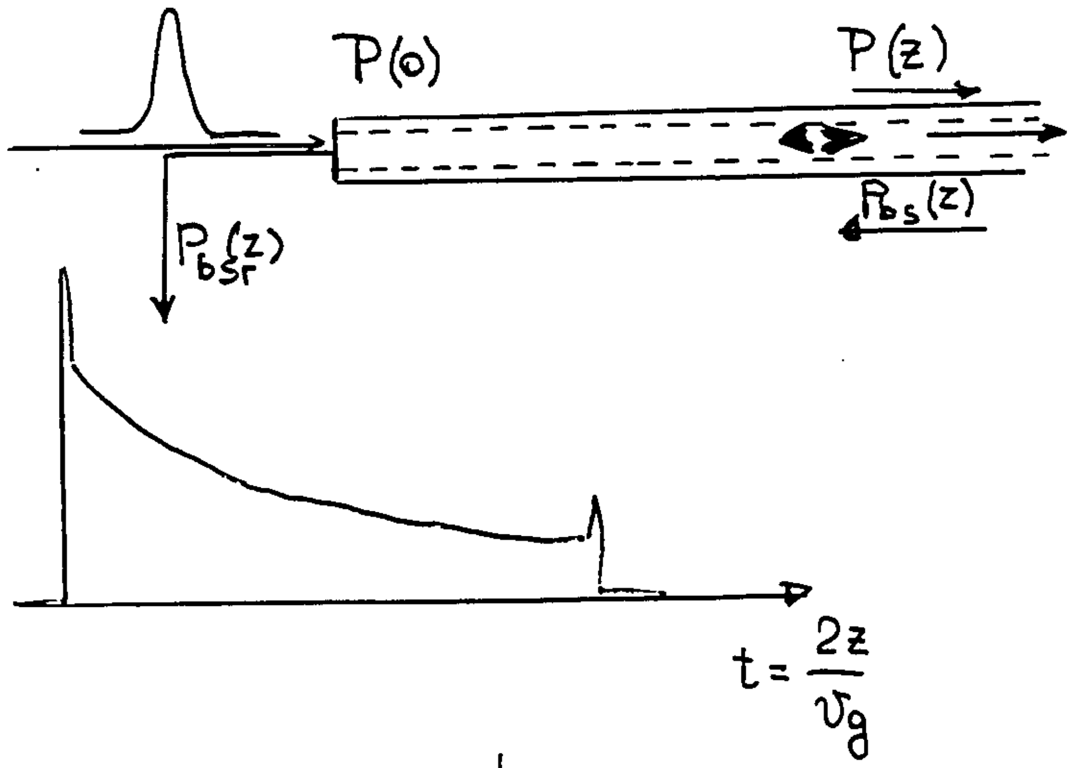
OPTICAL TIME DOMAIN REFLECTOMETRY (O.T.D.R.) -

AN ATTENUATION MEASUREMENT TECHNIQUE WHICH FINDS WIDE APPLICATION IN BOTH THE LABORATORY AND IN THE FIELD IS THE USE OF OPTICAL DOMAIN REFLECTOMETRY ALSO CALLED BACKSCATTERING. IT PROVIDES MEASUREMENT ON AN OPTICAL LINK DOWN ITS ENTIRE LENGTH GIVING INFORMATION ON THE LENGTH DEPENDENCE ON THE LINK LOSS. IN THIS SENSE IT IS SUPERIOR TO THE OPTICAL ATTENUATION MEASUREMENT WHICH ONLY TEND TO PROVIDE AN AVERAGE LOSS ON THE WHOLE LENGTH OF THE FIBER. WHEN THE ATTENUATION ON THE LINK VARIES WITH LENGTH, THE AVERAGED LOSS INFORMATION IS INADEQUATE. O.T.D.R. ALSO PERMITS TO MEASURE THE LOSS OF SPLICE AND CONNECTOR AS WELL

AS THE LOCATION OF ANY FAULTS ON THE LINK.

THE METHOD IS BASED ON THE MEASUREMENT AND ANALYSIS OF THE FRACTION OF LIGTH WHICH IS REFLECTED BACK WITHIN THE N.A. OF THE FIBER DUE TO RAYLEIGH SCATTERING. THE RAYLEIGH SCATTERING IS DUE TO THE DENSITY FLUCTUATIONS INTO THE GLASS AND IT IS ALMOST IN ALL THE DIRECTIONS.

THE BACKSCATTERING METHOD HAS THE ADVANTAGES OF BEING NON DESTRUCTIVE AND OF REQUIRING ACCESS TO ONE END OF THE OPTICAL LINK ONLY.



$$P(z) = P(0)\, exp^{-\alpha z}$$

α = ATTENUATION COEFFICIENT

$$P_{bs}(z) = K\, P(z) = K\, P(0)\, exp^{-\alpha z}$$

K = OPTICAL POWER FRACTION BACKSCATTERED
IT DEPENDS ON:

- RAYLEIGH SCATTERING COEFFICIENT
- GEOMETRICAL FIBER CHARACTERISTICS (FOR SINGLE MODE FIBERS (STEP-INDEX TYPE) is $\propto \frac{K' \lambda^2}{(n_1 W_0)^2}$ WHERE W_0 IS THE MODE SPOT RADIUS)

-INPUT OPTICAL PULSE WIDTH

THE VALUE OF K IS ABOUT 10^{-5} FOR F. SINGLE MODE

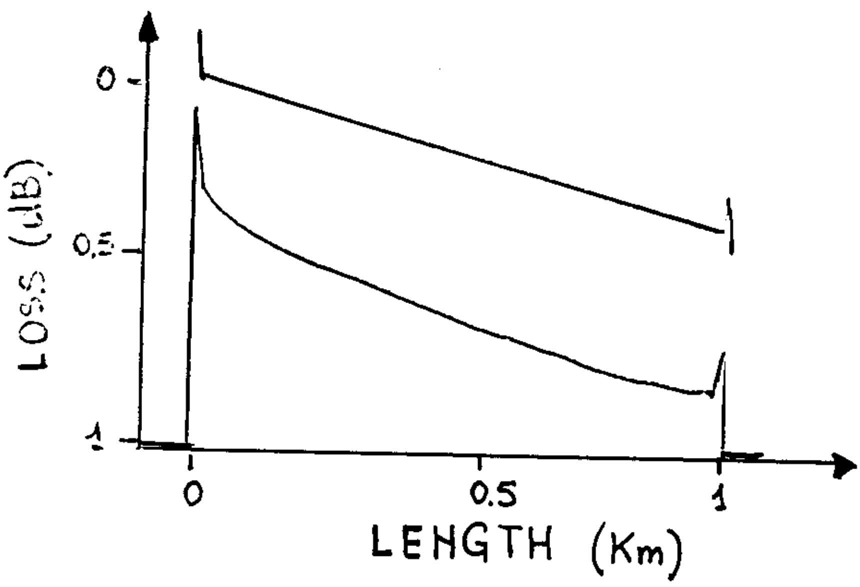
$$P_{bkr}(z) = K\,P(0)\,\exp^{-\alpha z}\exp^{-\alpha z} = K\,P(0)\,\exp^{-2\alpha z}$$

BACKSCATTERED POWER IS GUIDED BACKWARDS TILL TO THE FIBER INPUT END WITH A LOSS $e^{-\alpha z}$ AND A DELAY $t = \frac{2z}{v_g}$

WHERE v_g IS THE VELOCITY INTO THE FIBER

$v_g \simeq \frac{c}{n_1}$ (n_1 refractive index of the core)

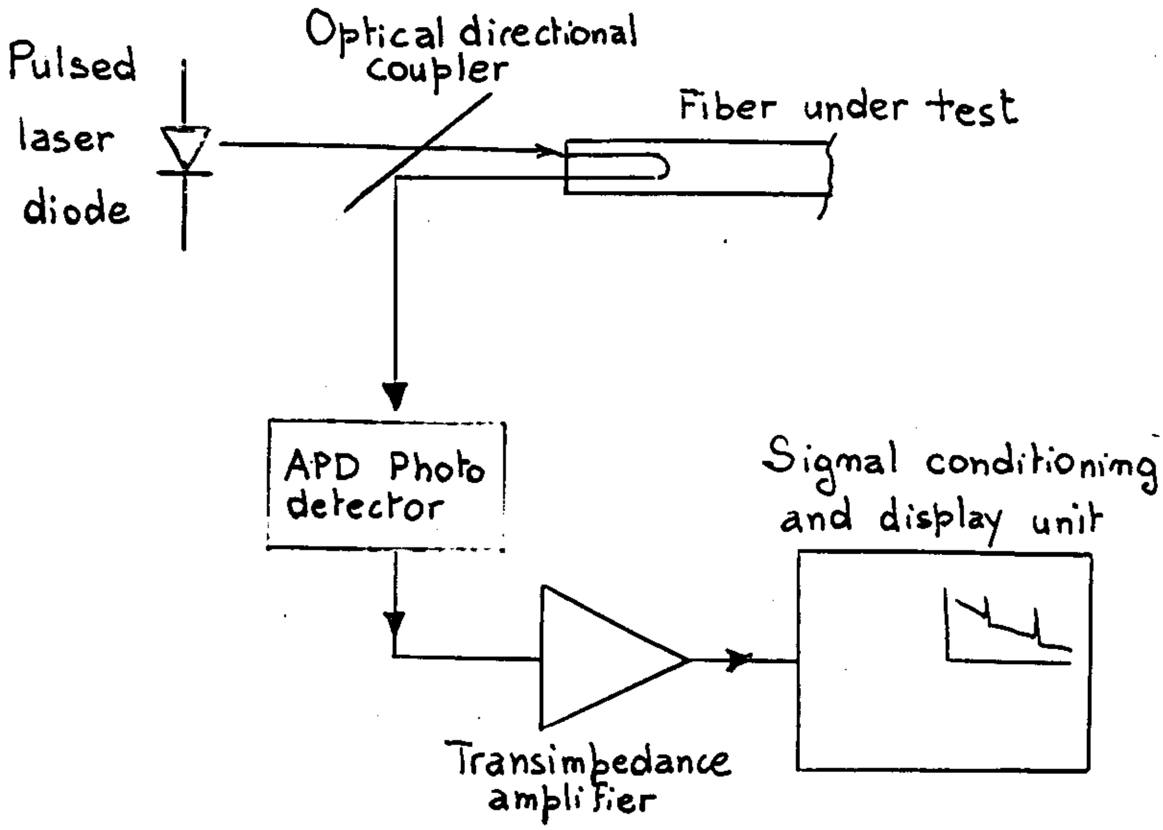
$$P_{bkr}(t) = K\,P(0)\,\exp^{-2\alpha\frac{v_g}{2}t}$$



$$P_{bkr} = K\,P(0)\,\exp^{-2\alpha z}$$

$$\log_{10} P_{bkr}(z) = \log_{10} K\,P(0) - \frac{2\alpha z}{\ln 10}$$

MEASUREMENT APPARATUS



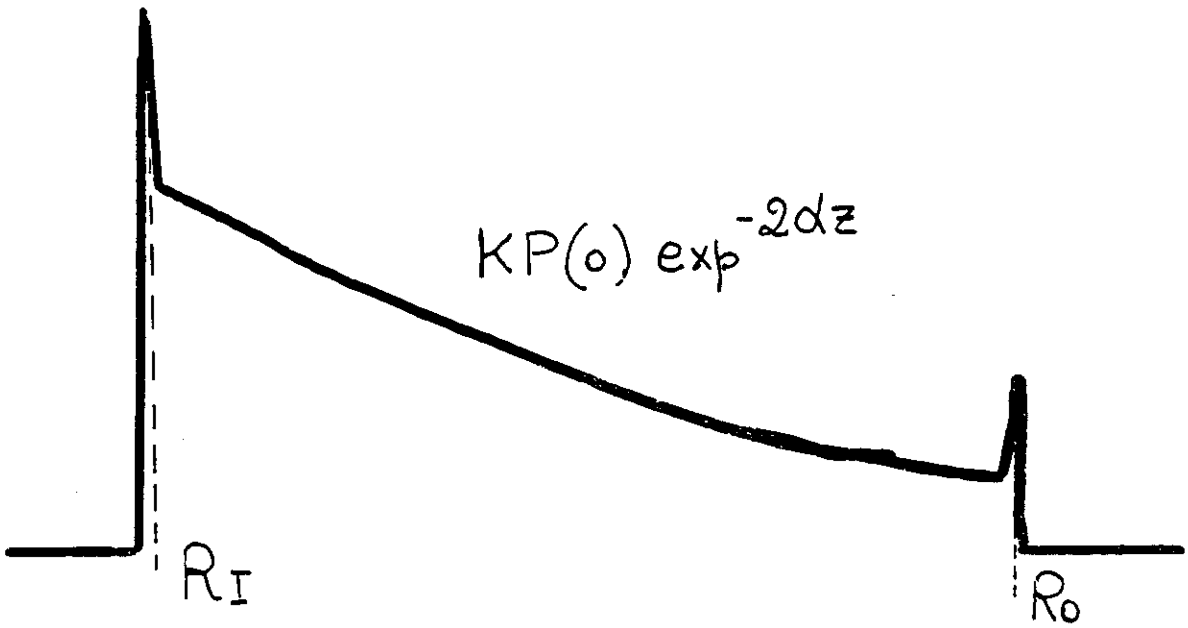
Source: - pulsed laser diode - peak power 1÷10 mW

- pulse width depends on the measurable range (for high resolution instrument from 3 to 10 ns, for long distance instrument 1 ÷ 4 μs).

Photodetector: Ge or InGaAs APD Photodetector

Signal conditioning: an average processor is included to obtain a better signal-to-noise ratio

REFLECTIONS



R_I AND R_o ARE THE REFLECTIONS AT THE INPUT AND THE OUTPUT FIBER END.

R_I IS FOR A GOOD BREAK ~ 4% OF P(0)

FROM AN EXPERIMENTAL POINT OF VIEW, A MAIN PROBLEM IS TO PREVENT THE REFLECTION FROM THE FIBER INPUT END FROM FALLING ONTO THE DETECTOR.

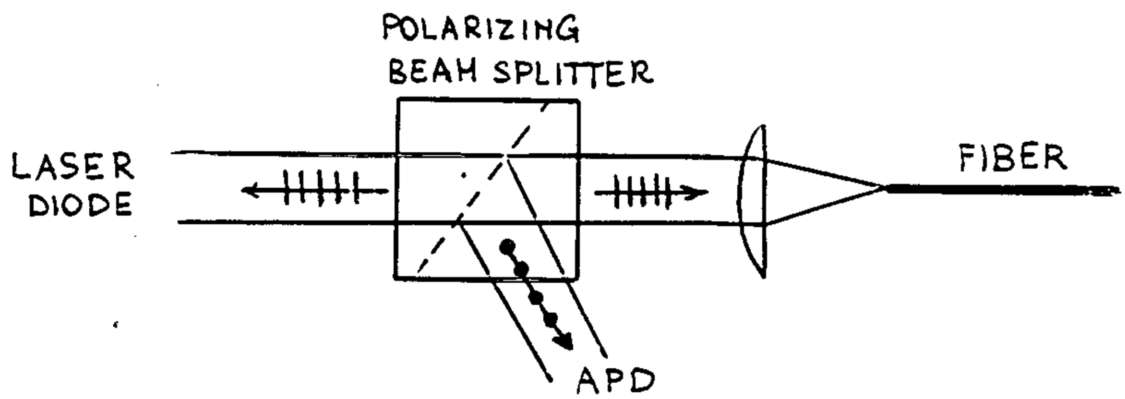
$$R_I \cong 0.04 \cdot P(0) \qquad P_{bkr} = 10^{-5}\, P(0)$$

$$R_I \simeq 4000\, P_{brk}$$

THE BACKSCATTERED POWER LEVEL IS 36dB BELOW THE 4% REFLECTION POWER: IF THE

SENSITIVITY OF THE DETECTOR- AMPLIFIER COMBINATION IS SUCH TO REVEAL THE WEAK USEFUL SIGNAL COMPLETE SATURATION IS CAUSED BY THE REFLECTED PULSE, RESULTING IN SEVERE DISTORSION OF THE EXP. SIGNAL.

TO DIVIDE THE SCATTERED POWER AND THE 4% REFLECTION POWER IS POSSIBLE TO USE FOR MULTIMODE FIBERS A POLARIZING DIRECTIONAL COUPLER.

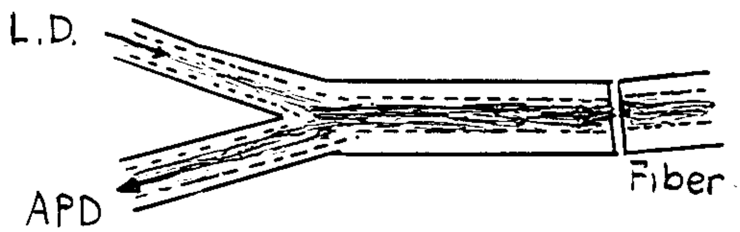


THE 4% REFLECTION POWER HAS THE SAME POLARIZATION THAN THE L.D. POWER, INSTEAD THE SCATTERED POWER IS NOT POLARIZED. THE BEAMSPLITTER SENDS ONLY THE NON-POLARIZED POWER ON THE APD DETECTOR.

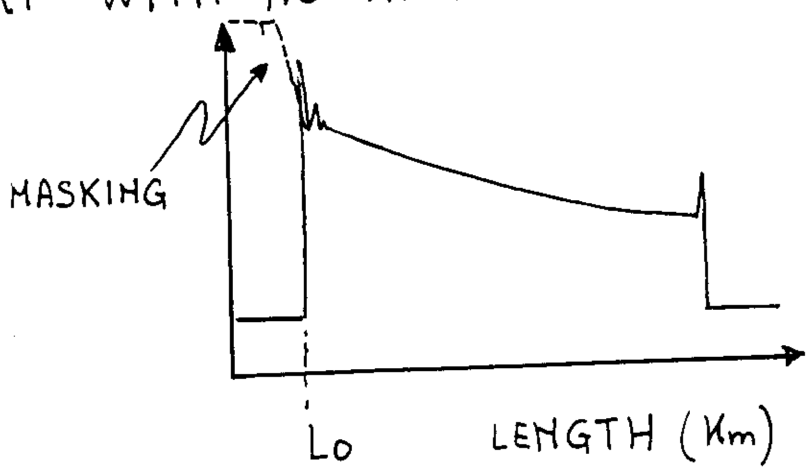
THE POLARIZING PRISM IS NOT USEFUL FOR SINGLE MODE FIBERS BECAUSE THEY MAINTAIN THE STATE OF POLARIZATION. IT IS POSSIBLE TO AVOID THE EFFECT OF REFLECTION BY

- OR USING AN Y COUPLER AND MASKING ELECTRONICALLY THE RECEIVING PART (DETECTOR AND AMPLIFIER)
- USING AN ACUSTO-OPTICAL DEFLECTOR.

USE OF Y COUPLER.



IT IS NECESSARY TO MASK THE RECEIVING PART WITH NO INFORMATION OF Lo OF FIBER.



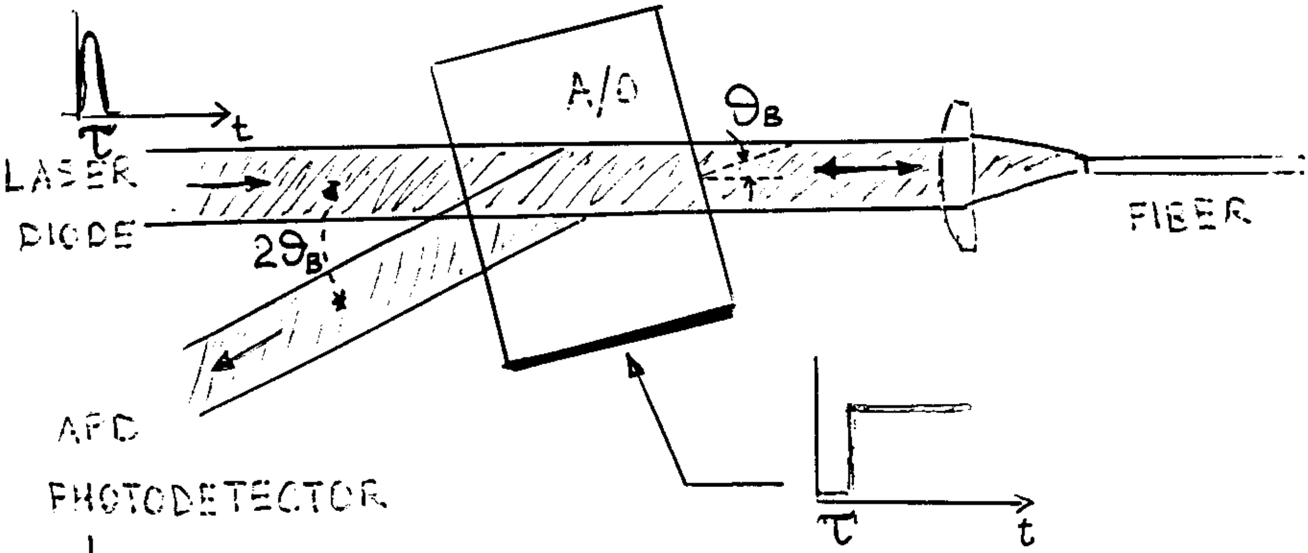
USE OF THE A/O DEFLECTOR

THIS DEVICE WHICH DEFLECT A LIGHT BEAM IS BASED ON THE DIFFRACTION OF LIGHT PRODUCED BY AN ACOUSTIC WAVE TRAVELLING THROUGH A TRANSPARENT MEDIUM. THE ACOUSTIC WAVE PRODUCES A PERIODIC VARIATION IN DENSITY (e.g. MECHANICAL STRAIN) ALONG ITS PATH WHICH GIVES RISE TO CORRESPONDING CHANGES IN REFRACTIVE INDEX IN THE MEDIUM.

ANY LIGHT BEAM PASSING THROUGH THE MEDIUM AND CROSSING THE PATH OF THE ACOUSTIC WAVE IS DEFLECTED BY AN ANGLE $2\theta_B$ WHERE θ_B IS THE ANGLE BETWEEN THE LIGHT BEAM AND THE ACOUSTIC BEAM-WAVEFRONT.

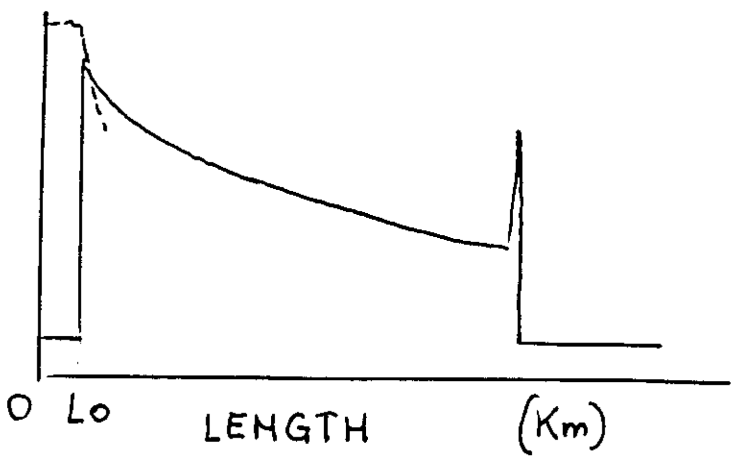
A TeO_2 CRYSTAL IS GENERALLY USED IN THIS DEVICE.

AN ELECTRIC SINUSOIDAL SIGNAL ($f \simeq 100$ MHz, $P = 1 \div 2$ W) IS NECESSARY TO OBTAIN THE ACOUSTIC WAVE IN THE CRYSTAL.

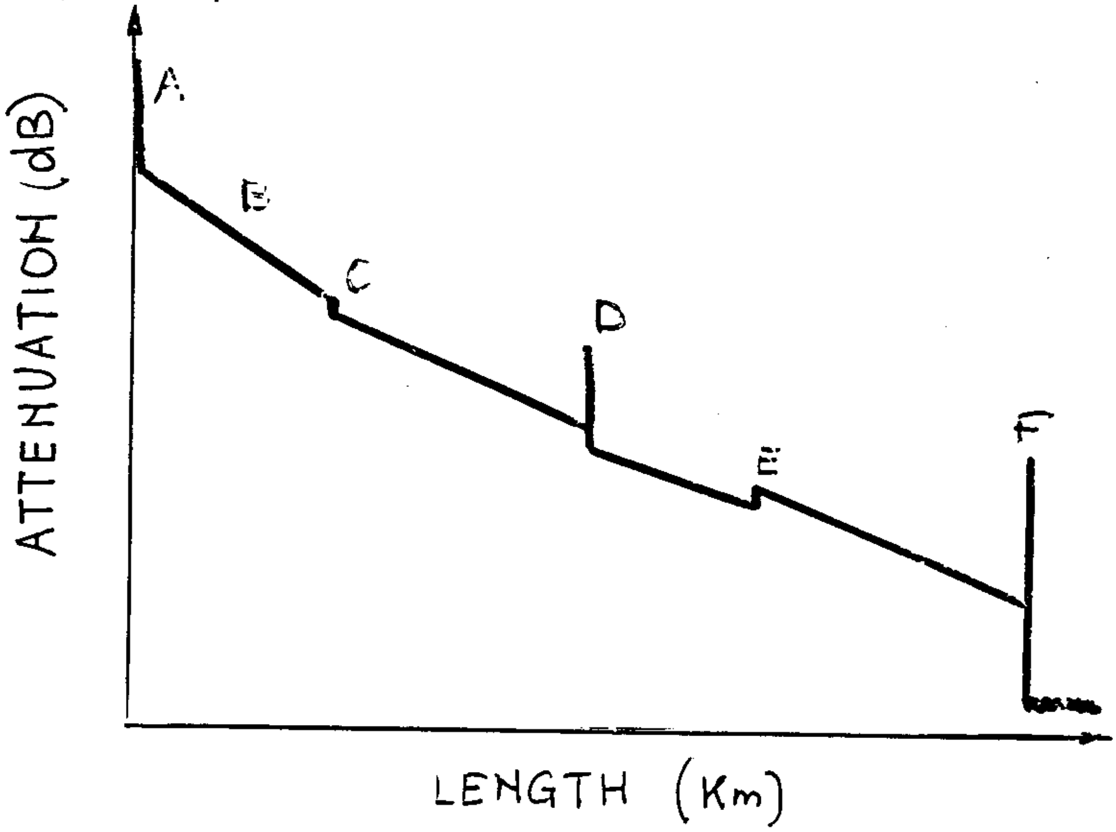


$0 \leq t \leq \tau$: THE OPTICAL PULSE OF THE LASER TRAVELS THE A/O MODU- LATOR AND ARRIVES ON THE FIBER. THE BACK-REFLECTION IS SEND ON THE LASER.

$t > \tau$: THE BACKSCATTERING SIGNAL IS DEFLECTED ON THE APD.



OPTICAL LINK MEASURED WITH AN O.T.D.R.



A : NEAR END FIBER REFLECTION

B : THE FIBER ATTENUATION IS THE SLOPE OF THE CURVE

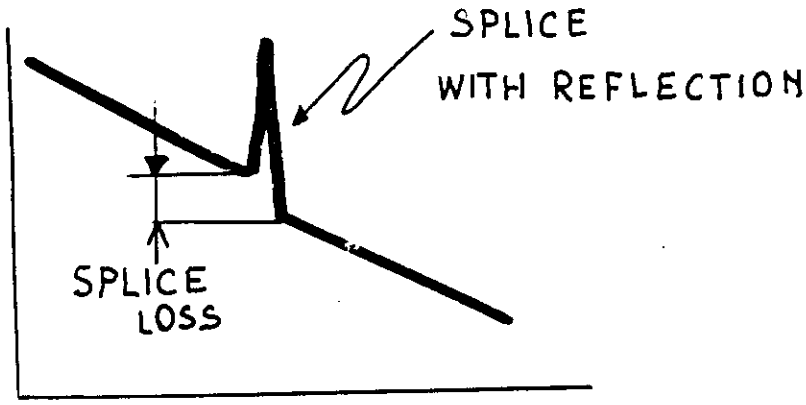
C : LOSS OF A SPLICE, ASSUMING IDENTICAL FIBERS

D : SPLICE LOSS WITH REFLECTION (e.g. MECHANICAL SPLICE OR CONNECTOR)

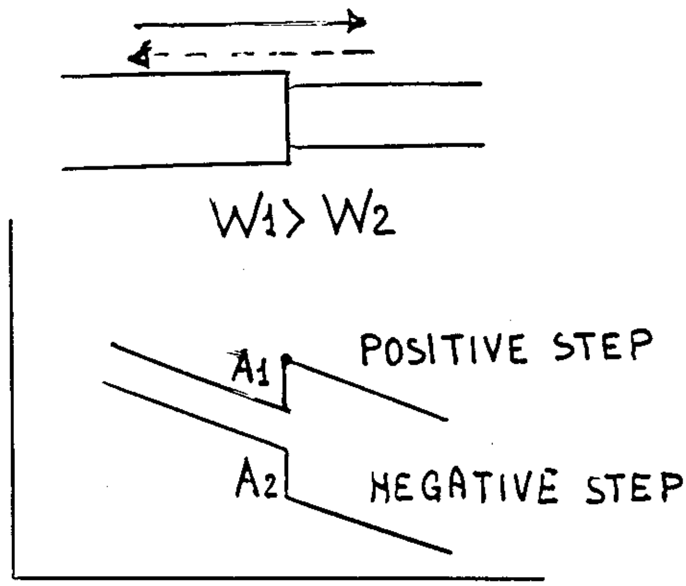
E : A POSITIVE STEP INDICATES A SPLICE BETWEEN TWO FIBERS WITH DIFFERENT N.A.

F : FAR END FIBER REFLECTION

Splices



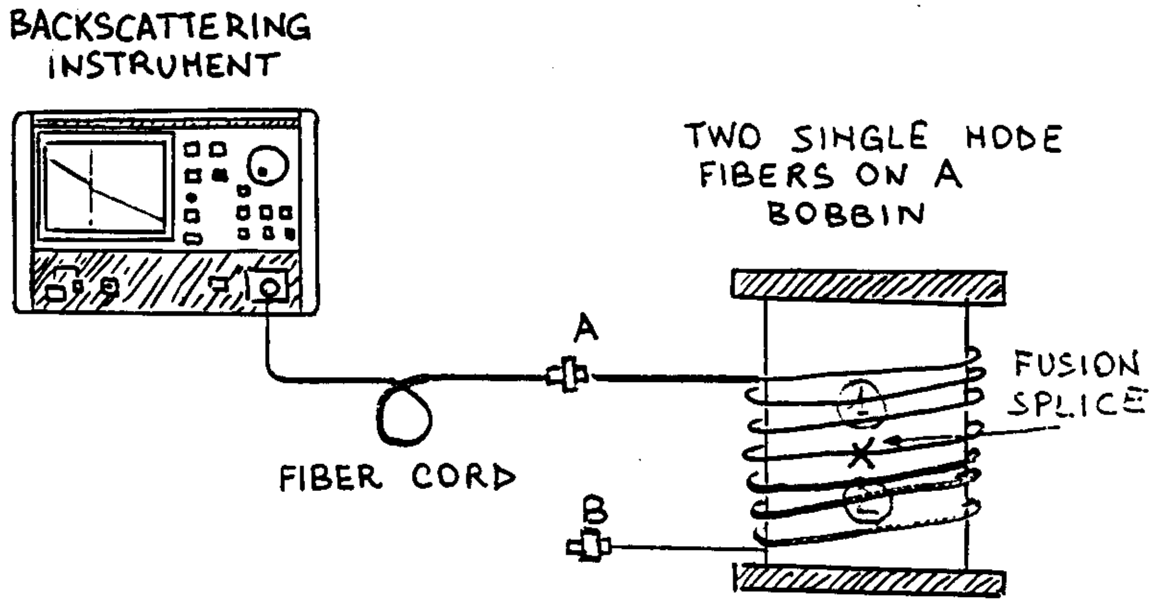
SPLICES BETWEEN DIFFERENT FIBERS BUT WITH EQUAL REFRACTIVE INDEX (n_1) AND DIFFERENT MODE SPOT RADIUS(W).



THE TRUE LOSS OF THE SPLICE IS THE MEAN VALUE OF THOSE MEASURED FROM THE TWO ENDS OF THE LINK.

$$A = \frac{A_1 + A_2}{2}$$

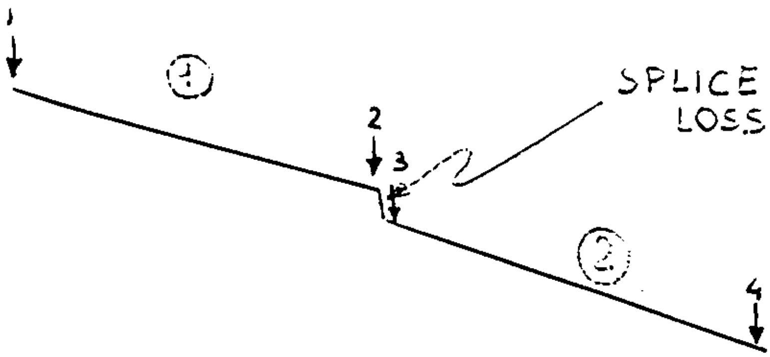
BACKSCATTERING MEASUREMENTS



SPECIFICATIONS:

WAVELENGTH	:	1.3 μm
FIBER UNDER MEASUREMENT	:	S.M.F.
PULSE WIDTH	:	3, 10, 100 ns
DYNAMIC RANGE	:	10 dB

-MEASUREMENT FROM THE END A

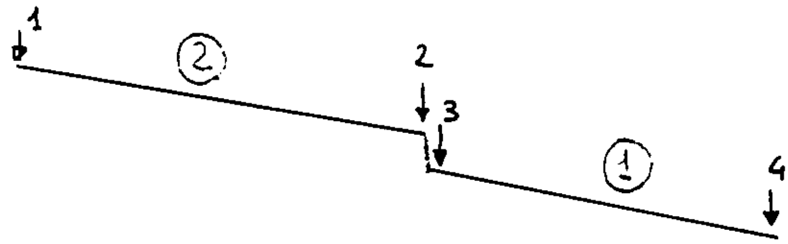


FIBER ①: THE ATTENUATION IS MEASURED BETWEEN THE MARKERS 1-2

FIBER ②: THE ATTENUATION IS MEASURED BETWEEN THE MARKERS 3-4

SPLICE LOSS: THE MEASUREMENT IS PERFORMED BETWEEN THE POINTS 2-3.

-MEASUREMENT FROM THE END B:



FIBER ②: THE ATTENUATION IS MEASURED BETWEEN THE MARKERS 1-2

FIBER ①: THE ATTENUATION IS MEASURED BETWEEN THE MARKERS 3-4

SPLICE LOSS: THE MEASUREMENT IS PERFORMED BETWEEN THE POINTS 2-3.