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TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

(5 February - 2 March 1990)

BANDWIDTH MEASUREMENTS

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CSELT
Torino, Italy

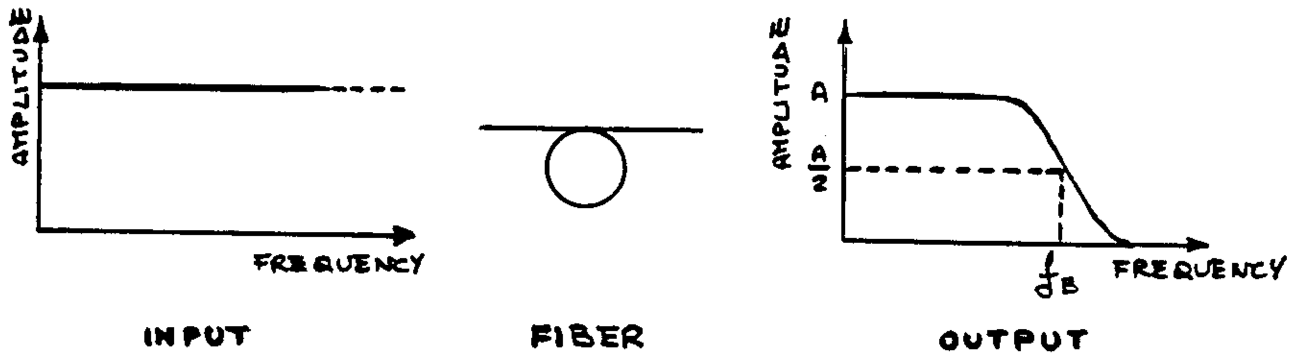
BANDWIDTH MEASUREMENTS

Sergio BIANCO - Giuseppe GALLIANO

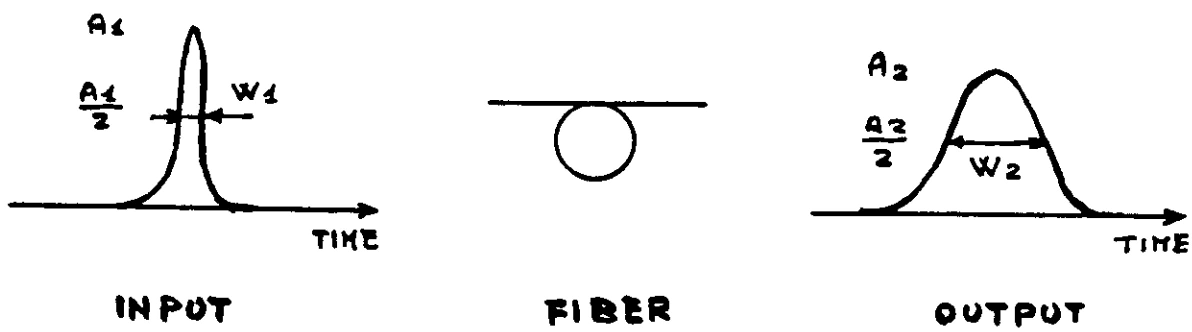
FIBER BANDWIDTH

THE FIBER BANDWIDTH IS DETERMINED AS THE -3 dB (OPTICAL) POINT OF THE AMPLITUDE / FREQUENCY FUNCTION, CORRESPONDING TO 50% SIGNAL :

FREQUENCY DOMAIN



TIME DOMAIN



THE FIBER BEHAVES LIKE A GAUSSIAN LOW-PASS FILTER ; ASSUMING A GAUSSIAN PULSE AT THE INPUT OF A FIBER, THE OUTPUT WILL ALSO BE

GAUSSIAN. THE FIBER DISPERSION Δt_f IS:

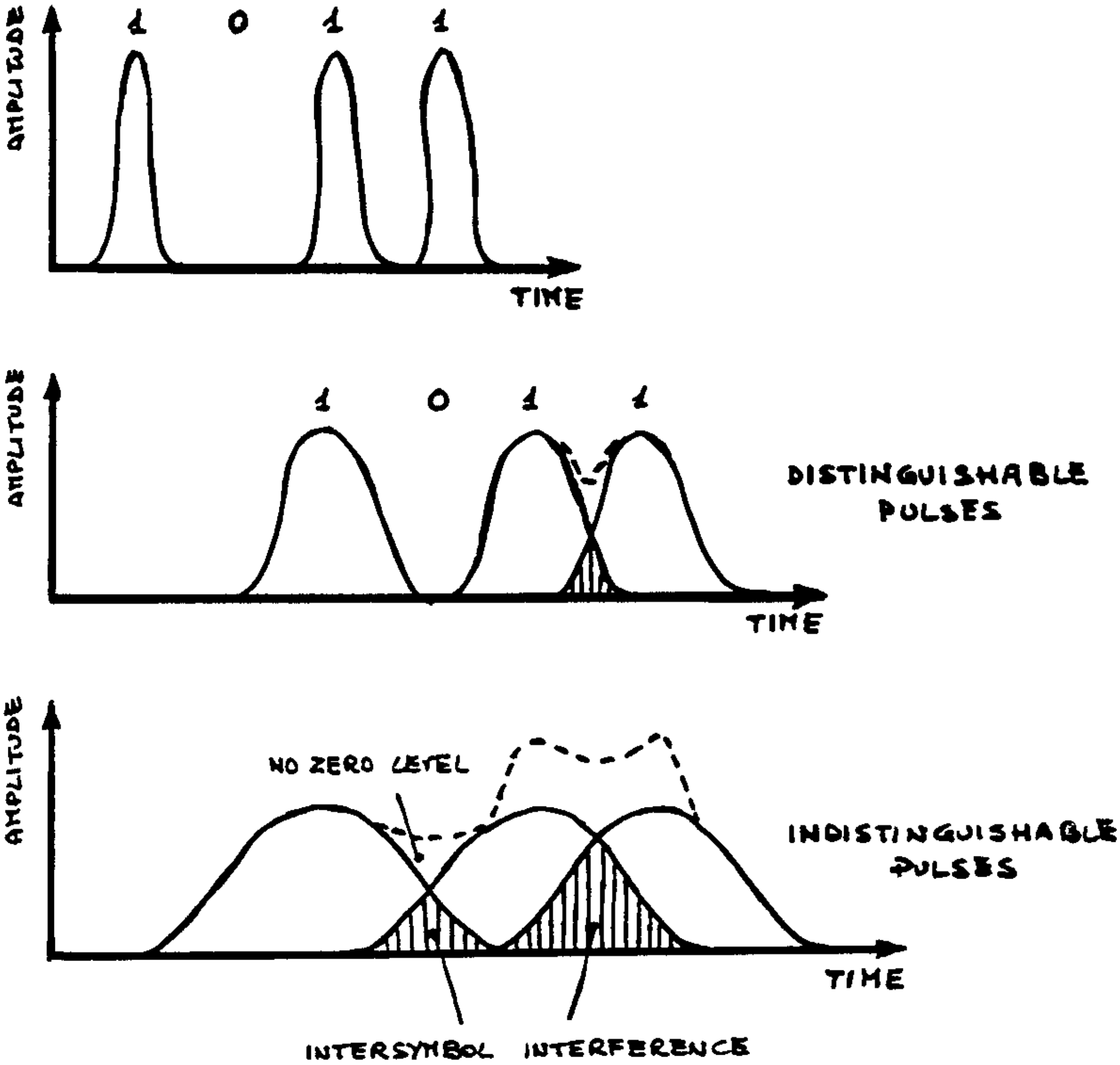
$$\Delta t_f = \sqrt{W_2^2 - W_1^2}$$

TO CONVERT DISPERSION Δt_f TO BANDWIDTH f_B:

$$f_B = \frac{0.44}{\Delta t_f}$$

FOR OTHER THAN GAUSSIAN SYSTEMS THE FOURIER TRANSFORM SHOULD BE USED TO CONVERT FROM TIME DOMAIN TO FREQUENCY DOMAIN.

FIBER BANDWIDTH CAUSES BROADENING (DISPERSION) OF THE TRANSMITTED OPTICAL SIGNAL AND LIMITS THE INFORMATION CARRYING CAPACITY OF THE FIBER.



THE OPTICAL PULSES BECOME INDISTINGUISHABLE AT THE END OF THE FIBER ; THIS EFFECT IS KNOWN AS INTERSYMBOL INTERFERENCE.

FIBER BANDWIDTH AND THE RELATED TOTAL DI-SPERSION (PULSE BROADENING) ARE CHARACTERI-ZED BY TWO EFFECTS :

- MULTIMODE DISPERSION
- CHROMATIC DISPERSION

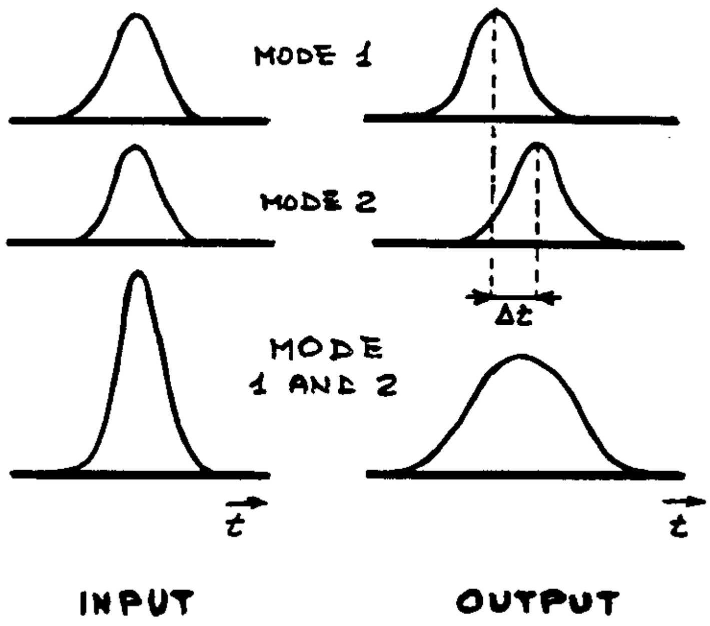
IN SINGLE MODE FIBERS ONLY CHROMATIC DISPERSION IS PRESENT.

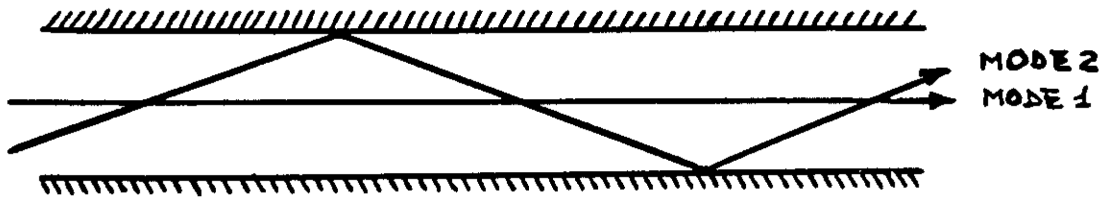
MULTIMODE DISPERSION

MULTIMODE DISPERSION IS PULSE BROADENING DUE TO OPTICAL POWER RUNNING VIA DIFFERENT WAVE-GUIDE OR MODES.

THIS BROADENING CAN BE ATTRIBUTED TO THE DIF-FERENCE IN PATH LENGTHS BETWEEN THE FUNDA-MENTAL ZERO-ANGLE MODE AND THE HIGHEST ORDER MODES.

NOW WE SUPPOSE TO HAVE A MULTIMODE STEP-INDEX FIBER WITH ATTENUATION EQUAL ZERO :





IN STEP-INDEX FIBERS ALL MODES TRAVEL AT THE SAME SPEED. IN GRADED-INDEX FIBERS THE REFRACTIVE INDEX PROFILE IS OPTIMIZED IN SUCH A WAY THAT THE FUNDAMENTAL ZERO-ANGLE MODE TRAVELS SLOWLY THAN THE HIGHEST ORDER MODES.

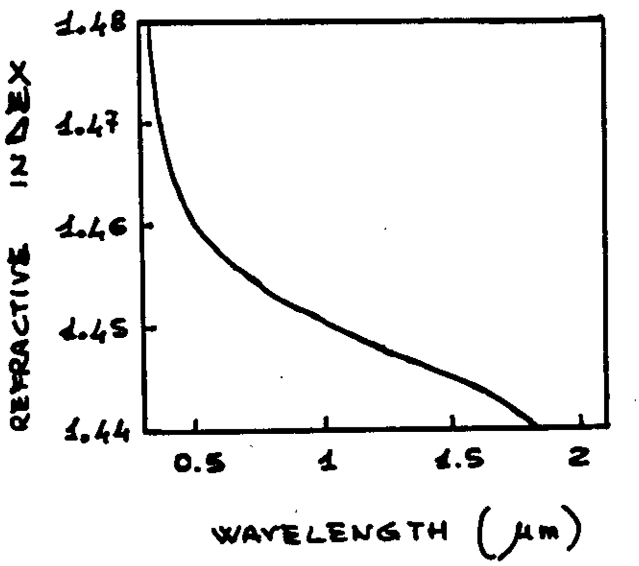
A BANDWIDTH OF 20 MHz·Km IS TYPICAL FOR STEP-INDEX FIBERS, WHILE GRADED-INDEX FIBERS BANDWIDTH IS NORMALLY HIGHER THAN 400 MHz·Km.

CHROMATIC DISPERSION

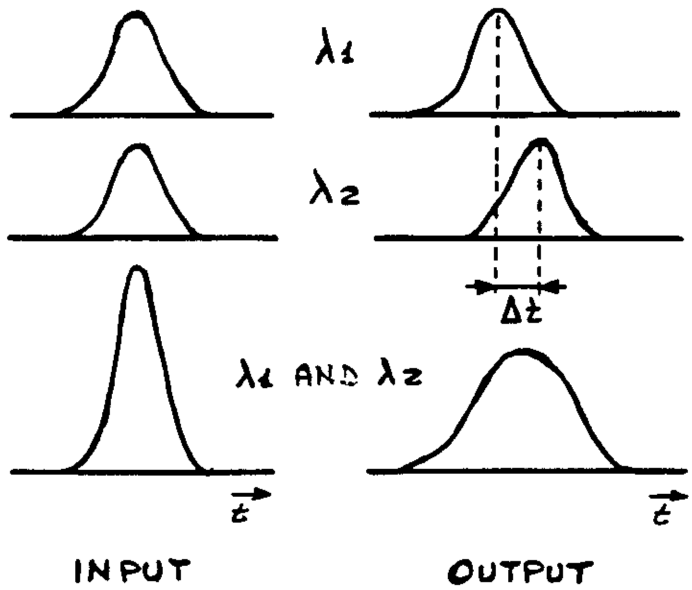
THE SPEED OF AN OPTICAL PULSE TRAVELLING IN A FIBER CHANGES AS ITS WAVELENGTH CHANGES.
TWO PHENOMENA CONTRIBUTE ADDITIVELY TO CHROMATIC DISPERSION :

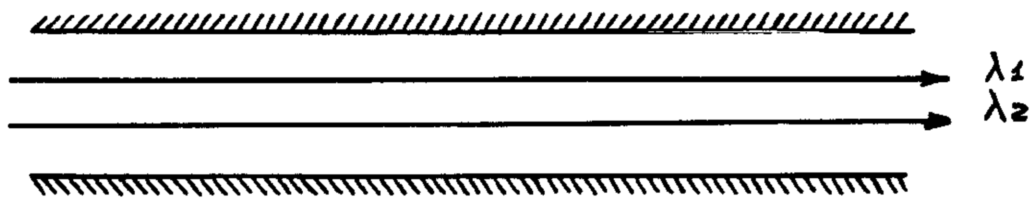
1) MATERIAL DISPERSION

IT IS DUE TO WAVELENGTH DEPENDANCE OF THE FIBER REFRACTIVE INDEX n AND THE ASSOCIATED DIFFERENCES IN SPEED OF LIGHT.



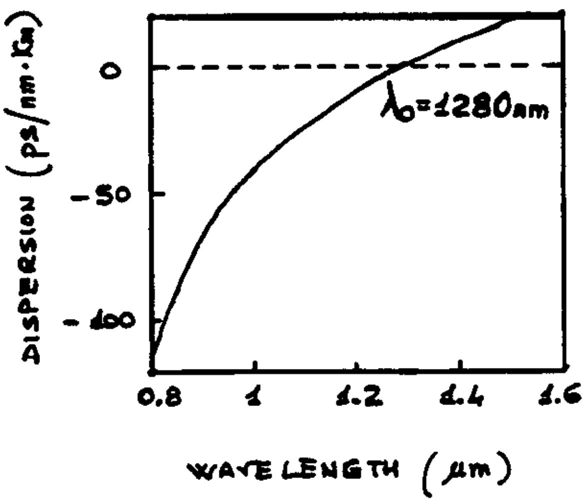
$$v(\lambda) = c/n(\lambda)$$





PRATICAL LIGHT SOURCES ARE NOT MONOCHROMATIC AND DIFFERENT COMPONENTS WITHIN THE SPEC_TRUM TRAVEL AT DIFFERENT SPEEDS.

ZERO-DISPERSION CORRESPONDS TO THE TURNING POINT OF THE n-CURVE (~ 1280 nm). BY ADDING GeO_2 THE ZERO-DISPERSION POINT SHIFTS TO LONGER WAVELENGTHS.

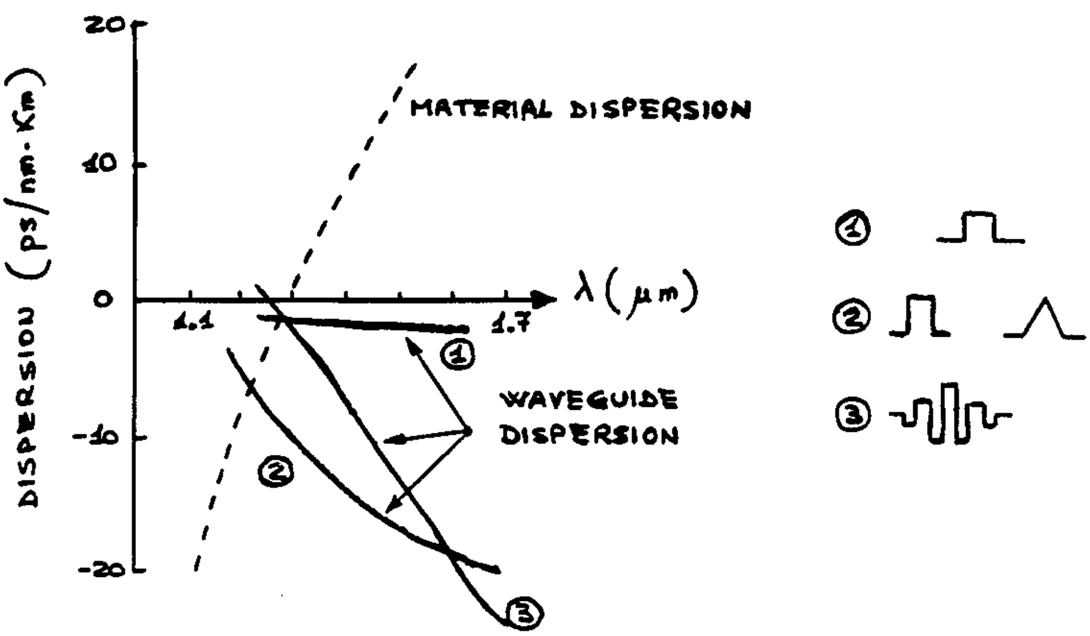


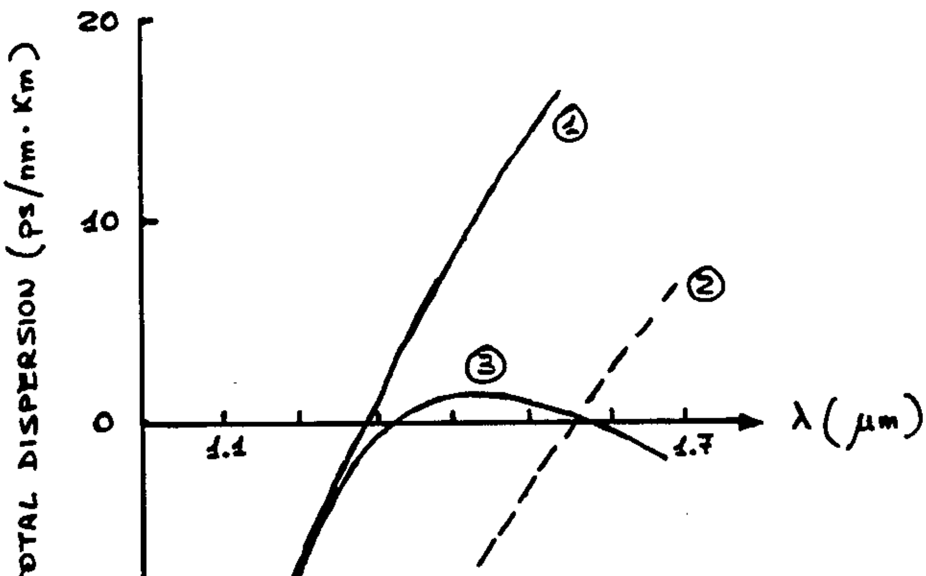
MATERIAL DISPERSION OF QUARTZ

2) WAVEGUIDE DISPERSION

IT CAN BE NEGLECTED IN MULTIMODE FIBERS.
IN SINGLEMODE FIBERS THE MODE DOESN'T TRAVEL ONLY IN THE CORE BUT IN THE CLADDING TOO; THEREFORE THE TIME DELAY VERSUS WAVELENGTH DEPENDS BY THE TYPE PROFILE AND THE CORE-CLADDING GAP OF THE REFRACTIVE INDEX.
WORKING ON THE PROFILE IS POSSIBLE DESIGN SINGLEMODE FIBERS OF THREE TYPES:

- CONVENTIONAL ($\lambda_0 \sim 1300$ nm)
- SHIFTED ($\lambda_0 \sim 1550$ nm)
- BROADBAND ($\lambda_{01} \sim 1300$ nm $\lambda_{02} \sim 1550$ nm)


DISPERSION (ps/nm·Km)
20
10
0
-10
-20
1.1
1.7
λ (μm)
MATERIAL DISPERSION
WAVEGUIDE
DISPERSION
①
②
③


TOTAL DISPERSION (ps/nm·Km)
20
10
0
-10
1.1
1.7
λ (μm)
①
②
③

BANDWIDTH MEASUREMENT
ON MULTIMODE FIBERS

TWO METHODS ARE USED TO EVALUATE THE BAND= WIDTH OF MULTIMODE OPTICAL FIBERS:

- FREQUENCY DOMAIN (DIRECT)
- TIME DOMAIN (INDIRECT)

THE SECOND IS AN INDIRECT METHOD BECAUSE IS NECESSARY USE A FOURIER TRANSFORMATION (USUAL= LY VIA F.F.T.) TO OBTAIN THE FREQUENCY CHARAC= TERISTIC.

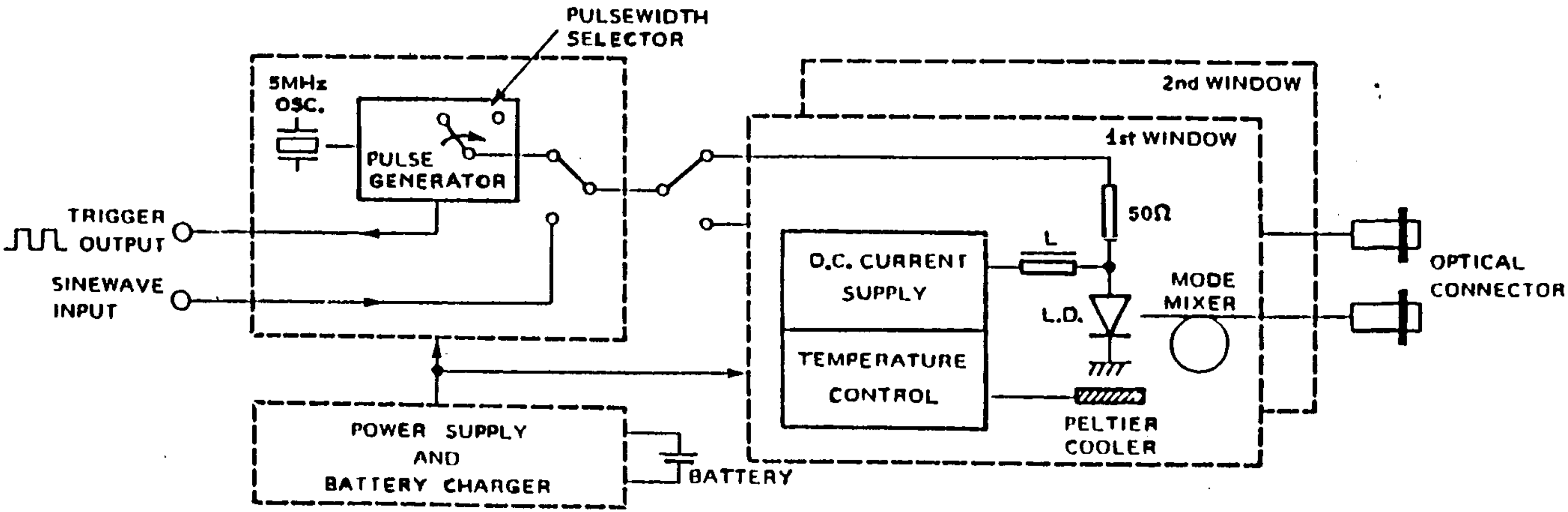
WITH THE FIRST TECHNIQUE THE LASER IS SINU= SOIDALLY MODULATED AT DIFFERENT FREQUENCIES USING A TUNED OSCILLATOR; A SPECTRUM ANALY= ZER IS USED TO OBTAIN THE FREQUENCY CHA= RACTERISTIC.

WITH THE TIME DOMAIN TECHNIQUE NARROW OPTICAL PULSES ARE LAUNCHED INTO THE FIBER FROM A LASER; THE PULSES TRAVEL DOWN THE LENGTH OF FIBER AND ARE BROADENED. THE OUTPUT PULSES ARE RECEIVED BY A SPEED PHOTODETEC= TOR (APD) AND ARE DISPLAYED ON A FAST SAM= PLING OSCILLOSCOPE.

THE CSELT MEASURING SET CAN BE USED BOTH IN THE FREQUENCY DOMAIN THAN IN THE TIME DOMAIN; IT HAS BEEN DEVELOPED SPECIALLY FOR FIELD POINT-TO-POINT MEASUREMENTS.
THE INSTRUMENT USEFUL RANGE IS ABOUT 30 dB AND 25 dB RESPECTIVELY FOR THE FIRST AND THE SECOND WINDOW, ON A 100 MHz BANDWIDTH LINE.
THE CSELT MEASURING SET IS CONSTITUTED BY:

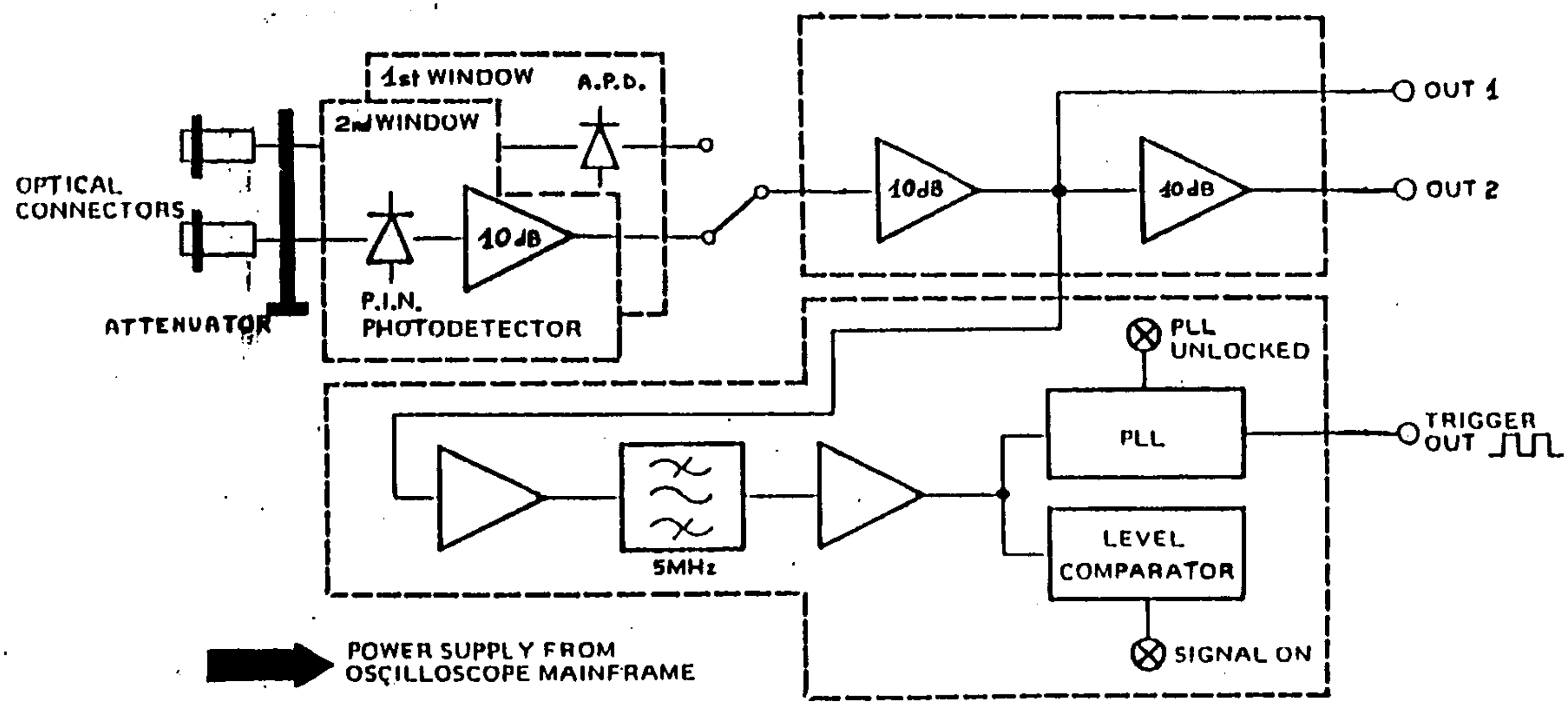
TRANSMITTER: AS OPTICAL SOURCES TWO COMMERCIAL C.W. LASER DIODES (FIRST AND SECOND OPTICAL WINDOW) ARE USED. A PROPER CIRCUIT STABILIZES THE LASER TEMPERATURE TO 20°C (± 0.1°C) AND PROVIDES THE LASER D.C. POLARIZATION CURRENT. FOR THE TIME DOMAIN MEASUREMENTS A PULSE GENERATOR PROVIDES THE ELECTRICAL PULSES FOR THE LASERS. AN INPUT PORT ALLOWS THE LASER TO BE DRIVEN BY SINUSOIDAL SIGNAL FOR FREQUENCY DOMAIN MEASUREMENTS. TO REALIZE A GOOD MEASURE REPRODUCIBILITY THE LASER PIGTAIL IS CONNECTED BY A SPRINGROOVE® SPLICE TO A MODE-MIXER THAT PERFORMS AN OVERFILLED LAUNCH.

Transmitter unit



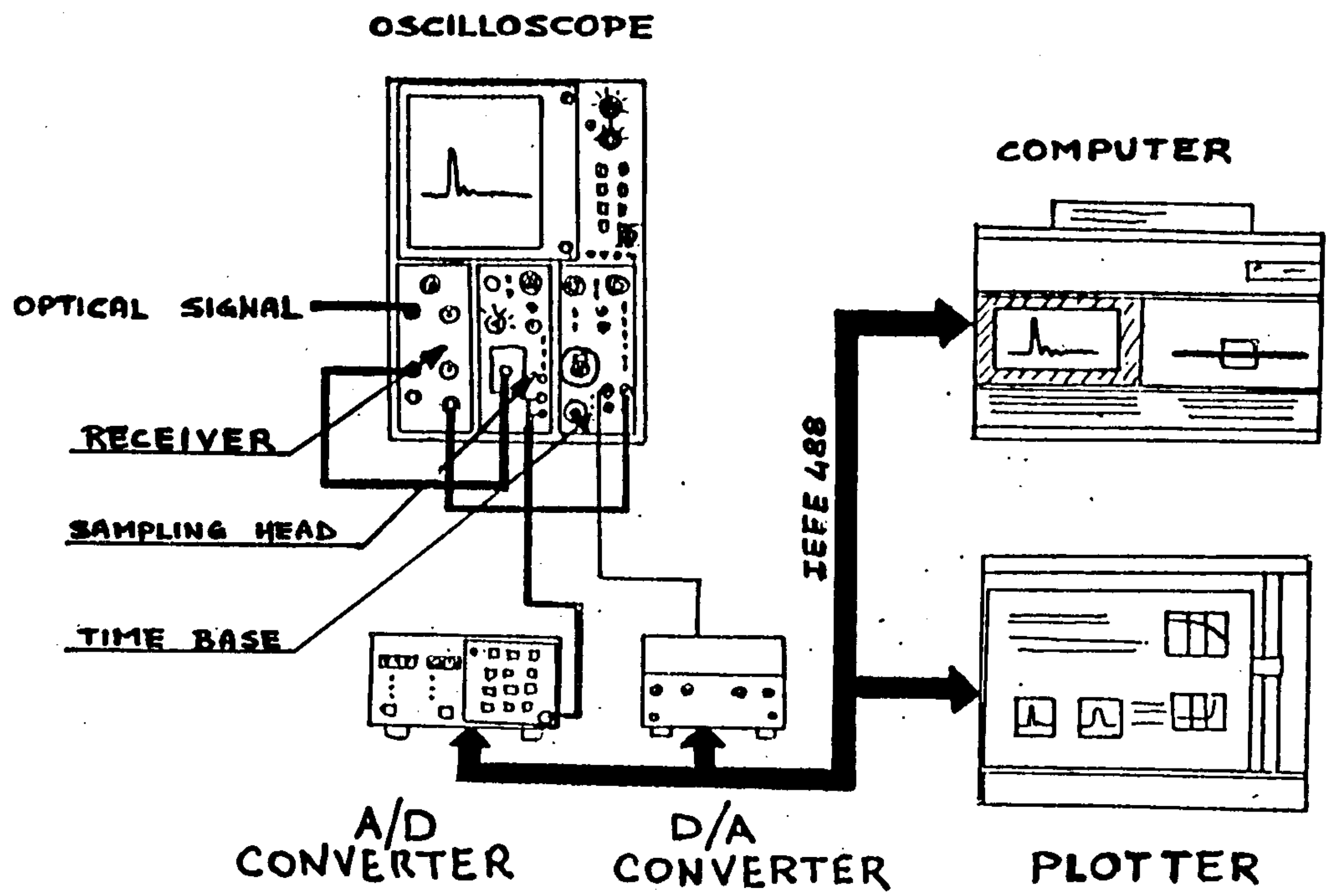
RECEIVER: IT IS HOUSED IN A PLUG-IN CHASSIS FOR A COMMERCIAL OSCILLOSCOPE MAIN-FRAME. AFTER THE TWO OPTICAL INPUT (FIRST AND SECOND WINDOW) A MINIATURE CONTINUOSLY VARIABLE OPTICAL ATTENUA-TOR HAS INSERTED. A SILICON APD IS USED AS PHOTODETECTOR FOR THE FIRST WINDOW AND A GaInAs PIN IS USED FOR THE SECOND WINDOW. TWO AMPLIFIERS FOLLOW THE PHOTODETEC-TORS AND THE OUTPUT SIGNAL CAN BE DERIVED FROM ANY OF TWO DIFFERENT POINTS. FOR FREQUENCY DOMAIN MEA-SUREMENTS THE FIRST OUTPUT CAN BE DIRECTLY CONNECTED TO SPECTRUM ANA-LYZER. AN ELECTRICAL CIRCUIT PROVIDES A SQUARE-WAVE (LOCKED ON THE RE-CEIVED PULSE TRAIN) USED LIKE TRIG-GER SIGNAL IN TIME DOMAIN MEASURE-MENTS.

Receiver unit



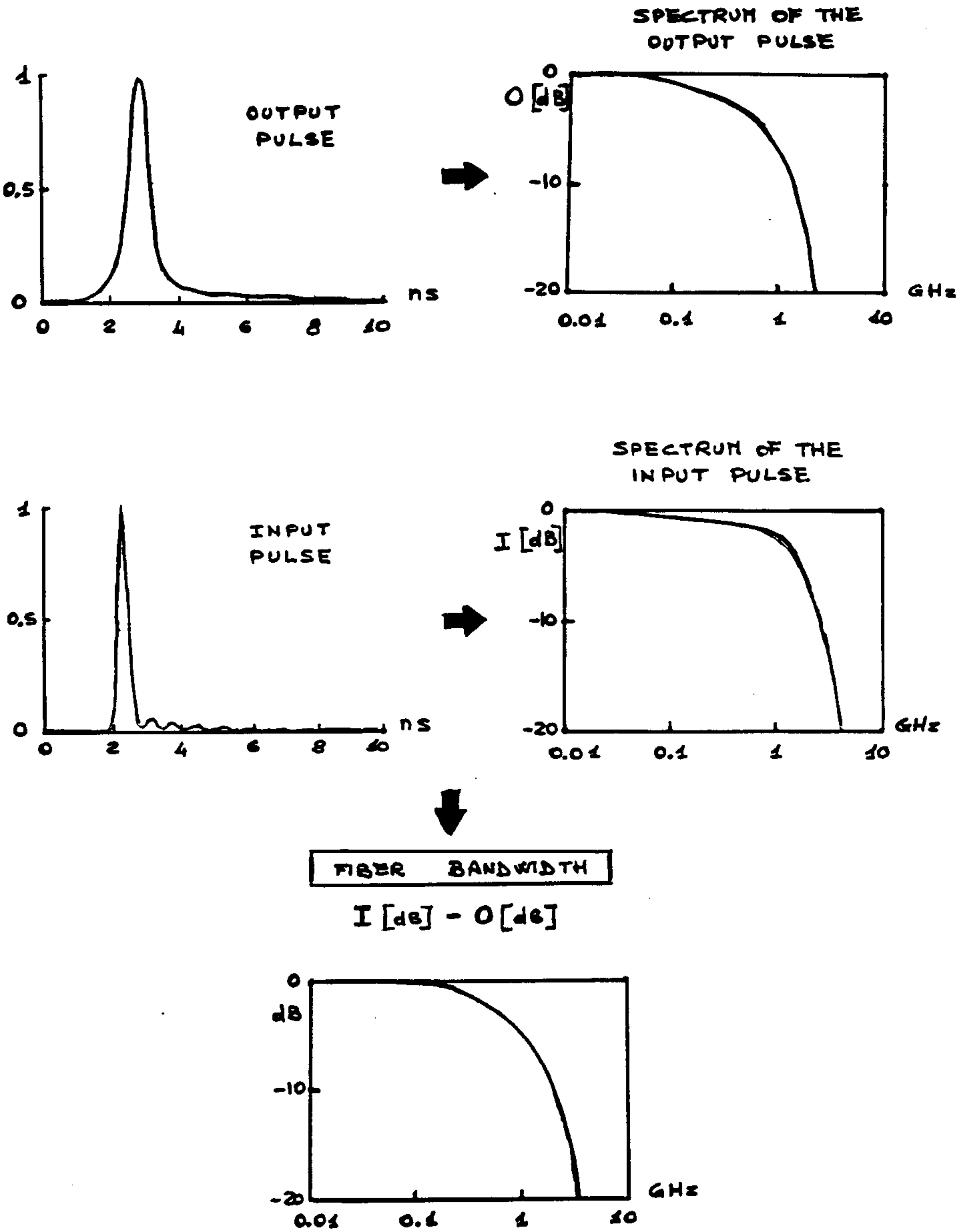
COMMERCIAL INSTRU-MENTS FOR TIME DO-MAIN MEASUREMENTS

AN OSCILLOSCOPE IS EQUIPPED WITH A SAMPLING HEAD TO DISPLAY THE NARROW PULSES. TO ACQUIRE FROM THE OSCILLOSCOPE THE DISPLAYED PULSE A PAIR OF D/A CONVERTERS IS USED. A COMPUTER IS USED TO CONTROL THE ACQUIRE PROCESS AND TO PERFORM THE FOURIER TRANS-FORMATION.


OSCILLOSCOPE
COMPUTER
OPTICAL SIGNAL
RECEIVER
SAMPLING HEAD
TIME BASE
IEEE 488
A/D CONVERTER
D/A CONVERTER
PLOTTER

MEASUREMENT TECHNIQUE

- TO ACQUIRE THE OUTPUT PULSE
- TO ACQUIRE THE INPUT PULSE
- TO PROCESS THE INPUT AND THE OUTPUT PULSES TO OBTAIN THE FIBER BANDWIDTH


SPECTRUM OF THE OUTPUT PULSE
OUTPUT PULSE
O [dB]
ns
GHz
SPECTRUM OF THE INPUT PULSE
INPUT PULSE
I [dB]
FIBER BANDWIDTH
I [dB] - O [dB]
dB

THE -3dB FREQUENCY POINT OF THE MEASURED AM-PLITUDE/FREQUENCY CHARACTERISTIC IS THE TOTAL BANDWIDTH OF THE FIBER (MULTIMODE + CHROMATIC BANDWIDTH).

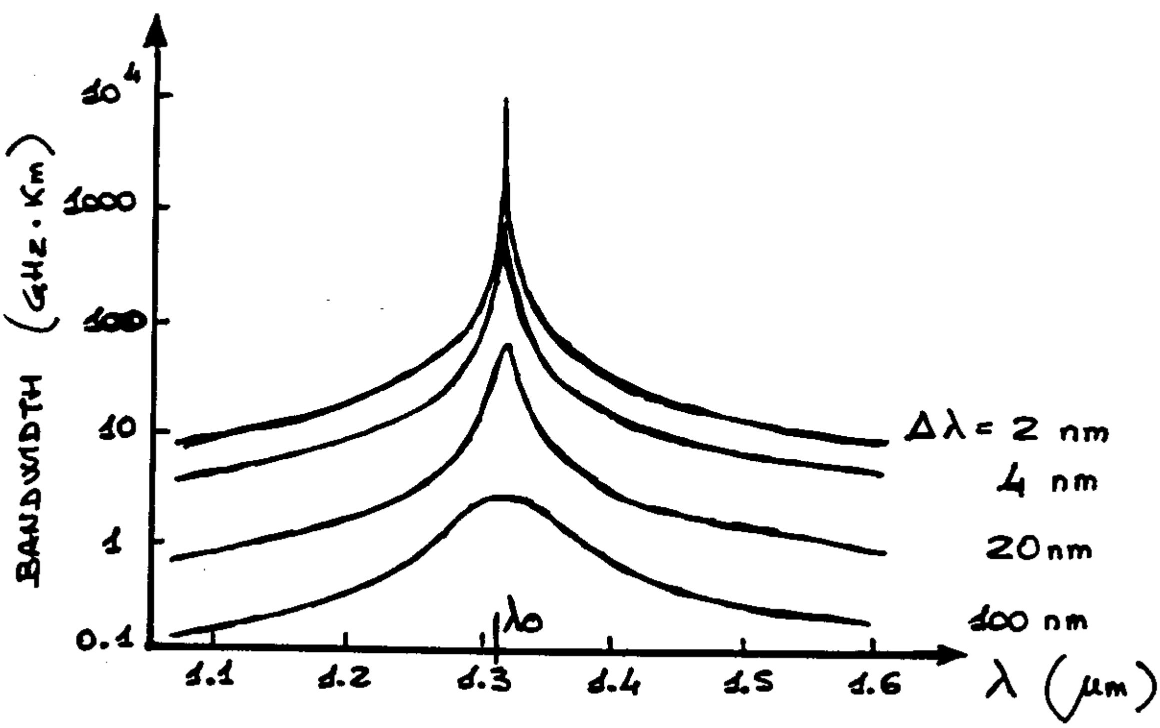
THE MULTIMODE BANDWIDTH IS THE COMMERCIAL DATA AND THE FIXED BANDWIDTH PARAMETER FOR MULTIMODE FIBERS.

THE CHROMATIC BANDWIDTH IS A FIBER VARIABLE PARA-METER WHICH DEPENDS BY THE SOURCE SPECTRAL WID-TH USED DURING THE MEASUREMENT AND BY THE FIBER CHROMATIC DISPERSION COEFFICIENT.

THIS SECOND PARAMETER CAN BE EVALUATED WITH A A CHROMATIC DISPERSION MEASUREMENT.

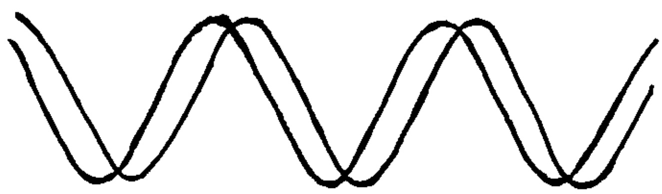
CHROMATIC DISPERSION MEASUREMENT

FOR SINGLE-MODE FIBERS THE CHROMATIC DISPERSION MEASUREMENT IS THE ONLY BANDWIDTH MEASUREMENT REQUIRES.
FOR MULTI-MODE FIBERS IT IS NECESSARY TO OBTAIN THE MULTIMODE BANDWIDTH FROM THE TOTAL DISPERSION MEASURED.
PULSE-BROADENING EFFECTS FOR CHROMATIC DISPERSION ARE TOO SMALL FOR TRADITIONAL PULSE RESPONSE MEASUREMENT TECHNIQUE.



SEVERAL ALTERNATIVE MEASUREMENT TECHNIQUES CAN BE USED TO CHARACTERIZE THE CHROMATIC DISPERSION; A CSELT MEASURING SET HAS BEEN DEVELOPED USING THE PHASE-SHIFT TECHNIQUE.

THE MEASUREMENT IS PERFORMED BY SINUSOIDALLY MODULATING THE SOURCE (LED) AND MEASURING PHASE DELAY BETWEEN THE VARIOUS WAVELENGTHS WHICH ARE SELECTED BY MONOCHROMATOR.



THE PROPAGATION DELAY BETWEEN THE WAVELENGTHS CAN BE OBTAINED USING:

$$\tau(\lambda) = \frac{\phi(\lambda)}{2\pi f}$$

WHERE f IS THE LED MODULATING FREQUENCY.

THE FIRST DERIVATIVE OF $\tau(\lambda)$ RESPECT TO WAVELENGTH IS THE CHROMATIC DISPERSION:

$$c(\lambda) = \frac{d\tau(\lambda)}{d\lambda}$$

BEFORE COMPUTING THE DERIVATIVE A FIT OF THE DELAY EXPERIMENTAL POINTS IS DONE USING A SELLMEIER FUNCTION :

$$\tau(\lambda) = A\lambda^{-2} + B + C\lambda^{2}$$

FOR MULTIMODE FIBERS AND CONVENTIONAL SINGLE MODE FIBERS OR A PARABOLIC FUNCTION :

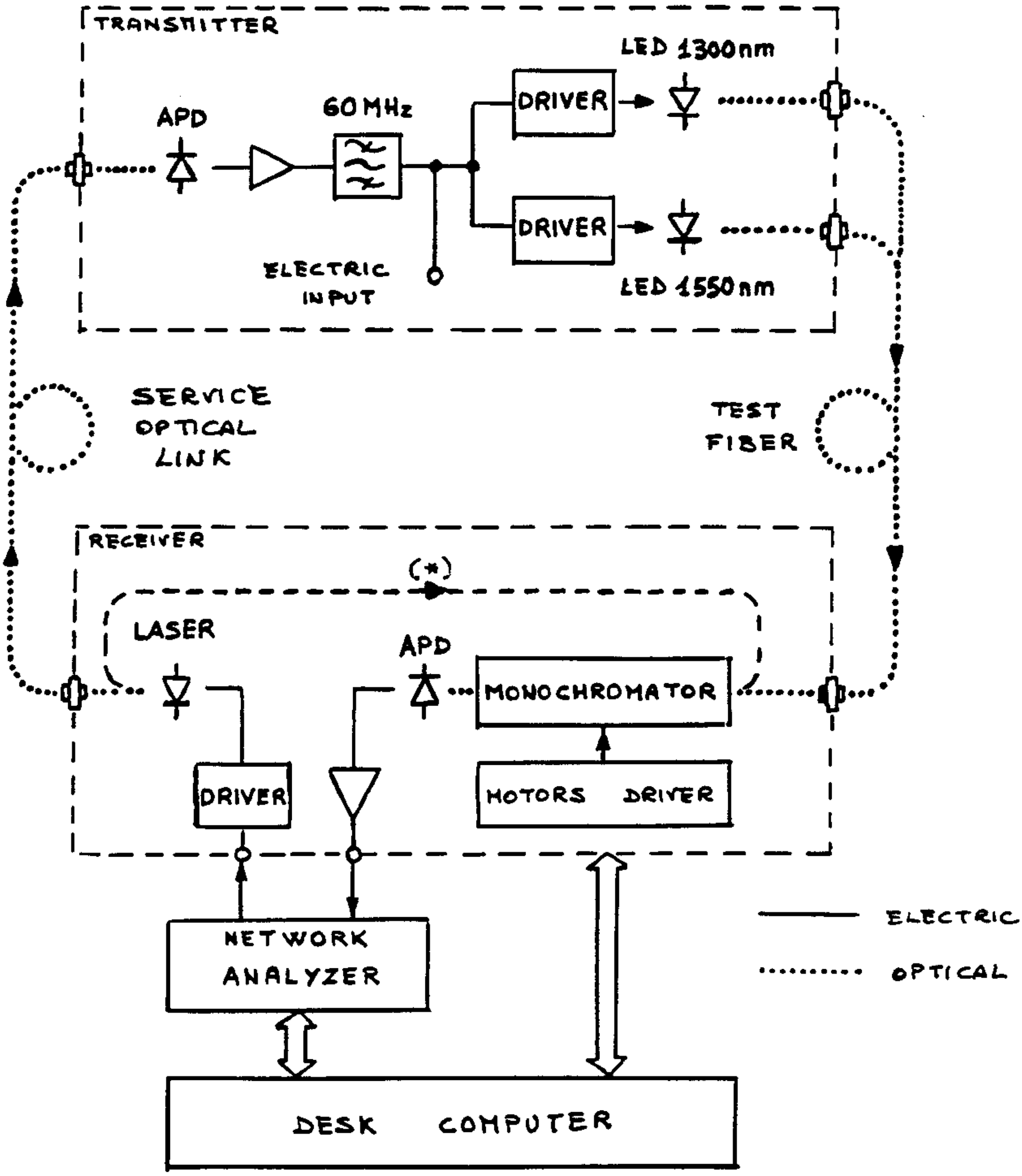
$$\tau(\lambda) = A + B\lambda + C\lambda^{2}$$

FOR SHIFTED SINGLE MODE FIBERS .

THE USEFUL RANGE OF THE CSELT INSTRUMENT IS ABOUT 30 dB ; IT CAN MEASURE OPTICAL LINKS TILL TO 75 Km IN THE SECOND WINDOW AND ≤ 20 Km IN THE THIRD WINDOW .

THE CSELT MEASURING SET IS CONSTITUTED BY :

TRANSMITTER : AS OPTICAL SOURCES TWO COMMER- CIAL InGaAsP EDGE-EMETTING LEDs (SECOND AND THIRD WINDOW) ARE USED; THEY ARE MOUNTED IN A DUAL IN LI- NE PACKAGE WITH A MINIATURE THERMOELECTRIC COOLER . A PROPER CIRCUIT STABILIZES THE LED TEMPE- RATURE (± 0.5 °C FROM 0°C TO 40°C) TO OBTAIN A STABLE PHASE DU-



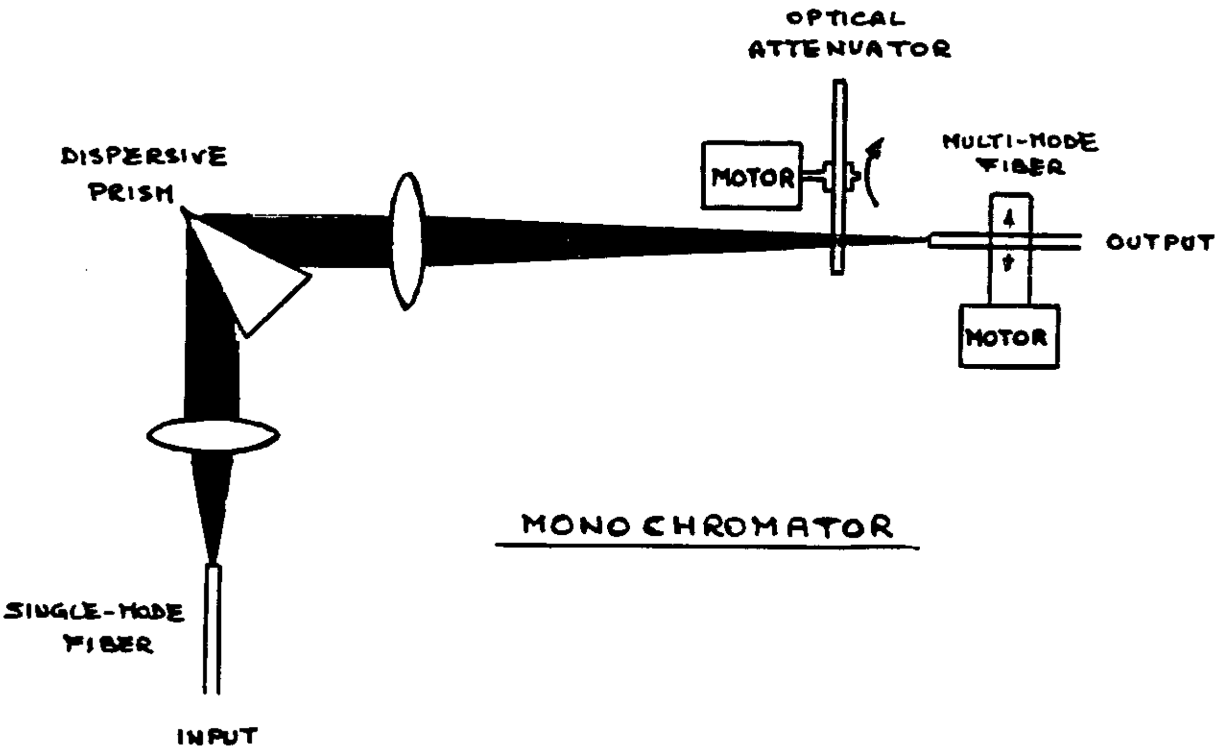
(*) ONLY FOR MONOCHROMATOR CALIBRATION

SCHEMATIC DIAGRAM OF THE CHROMATIC DISPERSION SET UP

RING THE MEASUREMENT ; ANOTHER CIRCUIT PROVIDES TO DRIVE THE SOUR= CES.

THE TRANSMITTER CAN RECEIVE THE SI= NUSOIDAL MODULATING SIGNAL (60 MHz) BOTH VIA AN ELECTRIC INPUT (LABORA= TORY MEASUREMENTS) THAN VIA AN OP= TICAL INPUT (FIELD POINT TO POINT MEASUREMENTS). IN THIS SECOND CA= SE A GERMANIUM APD PHOTODETEC= TOR, AN AMPLIFIER AND AN ELECTRIC FILTER ARE USED TO OBTAIN THE SINUSOIDAL MODULATING SIGNAL.

RECEIVER : A COMPACT MONOCHROMATOR HAS BEEN DEVELOPED BY CSELT USING A HIGH= LY DISPERSIVE ZnSe PRISM AND TWO STEPPING MOTORS. THE FIRST ONE SE= LECTS THE SEVERAL WAVELENGTHS USING A MULTIMODE FIBER, THE SECOND ONE TURNS A CIRCULAR OPTICAL ATTE= NUATOR TO OBTAIN (FOR EVERY WAVE= LENGTH) THE SAME OPTICAL LEVEL ON THE PHOTODETECTOR BOTH DURING THE FIBER THAN THE SYSTEM



MONOCHROMATOR

PHASE MEASUREMENT. THE MONOCHROMATOR RESOLUTION IS ABOUT 5 nm IN THE SECOND WINDOW AND 9 nm IN THE THIRD WINDOW. AT THE OUTPUT OF THE MONOCHROMATOR THERE ARE A InGaAs APD PHOTODETECTOR AND A TRANSIMPEDANCE AMPLIFIER.

IN THE RECEIVER THERE IS ALSO A LASER (λc = 1294 nm) USED TO SEND THE SINUSOIDAL MODULATING SIGNAL (60 MHz) TO THE TRANSMITTER USING A SERVICE OPTICAL LINK (DURING FIELD POINT TO POINT MEASUREMENTS). THIS SOURCE (NARROW SPECTRAL WIDTH) IS USED

TO OBTAIN THE MONOCHROMATOR CALIBRA-
TION TOO. THIS PRELIMINARY MEASURE-
MENT AVOIDS TO MAKE WAVELENGTH MI-
STAKES FOR THE TEMPERATURE DEPEN-
DANCE OF THE PRISM REFRACTIVE IN-
DEX. IN FACT A FIXED POSITION OF THE
STEPPING MOTOR, EQUIPPED WITH THE MUL-
TIMODE FIBER, DETECTS DIFFERENT WA-
VELENGTHS WHEN THE TEMPERATURE
CHANGES.

COMMERCIAL INSTRUMENTS: A NETWORK ANALYZER IS USED TO GENERA-
TE THE SINUSOIDAL SIGNAL AND TO MEA-
SURE THE PHASE FOR EVERY WAVELEN-
GTH. A COMPUTER IS USED TO CONTROL
THE MEASUREMENT PROCESS AND TO PER-
FORM THE CHROMATIC DISPERSION COM-
PUTING.

MEASUREMENT TECHNIQUE

- MONOCHROMATOR CALIBRATION
- TO ACQUIRE THE FIBER PHASE DELAY
- TO ACQUIRE THE SYSTEM PHASE DELAY
- TO PROCESS THE PHASE DELAYS TO OBTAIN THE FIBER CHROMATIC DISPERSION

Instrument for field bandwidth measurements on optical fibres

S. Bianco, A. Bollero, G. Galliano, M. Titli (*)

An instrument for time-domain bandwidth measurements both in the first and in the second window is described. The transmitter uses two CW diode lasers driven by selectable-width pulses at 5MHz. In the receiver a PLL circuit to trigger the oscilloscope is employed. The range in field point-to-point measurements is about 30dB and 25dB respectively for the first and the second window, on a 100MHz bandwidth line.

1. Introduction

A new versatile instrument for bandwidth measurements both in the first and in the second window on multimode optical fibres has been developed at CSELT. The instrument, specifically intended for field point-to-point measurements, operates in the time domain but it is possible to use it also in the frequency domain.

CSELT experience on field bandwidth instruments started some years ago with a first window only instrument [1], manufactured in some units and used successfully to characterize several experimental optical links. In this first instrument a low cost pulsed diode laser, driven by an avalanche transistor [2], was used, resulting in pulses having remarkable peak power (about 50 mW into a 50 μm core) short duration (300-400 ps at 50% of the peak) and repetition rate bounded to a few kilohertz by thermal limits. At the receiving side a system composed by a variable optical attenuator, an APD, a wideband amplifier and a delay line (for triggering problems) was used. The dynamic range was 40 dB simulating the fibre by an optical attenuator and 30 dB for a 100 MHz bandwidth link.

In developing a new instrument suitable also for second window fibres, the use of CW lasers instead of pulsed ones has been decided. The formers offer, besides a wider availability on the market and lower temperature control requirements, the following advantages:

— no restriction in the pulsewidth and shape;

— no time jitter between the driving and optical pulses;

— high repetition rate allowable.

This permits to choose the pulsewidth more suitable for the link under test and to avoid the delay line in the receiver. On the other side the emitted power is lower and in the first window the cost can be remarkably higher.

(*) P.i. Sergio Bianco, P.i. Adriano Bollero, Dr. Giuseppe Galliano, Dr. Mario Titli, CSELT, Torino.

2. Transmitter unit

The transmitter block diagram is shown in Fig. 1. As optical sources two commercial CW laser diodes (λ = 850 nm and λ = 1300 nm), each mounted in a dual in line package with a miniature thermoelectric cooler, are used. A proper circuit stabilizes the laser temperature to 20 °C and provides the laser D. C. polarization current.

The pulse generator includes a quartz oscillator (f = 5MHz) followed by a pulse forming circuit and provides 2V electrical pulses on the 50Ω load. The optical pulse train injected into the fibre is shown in Fig. 2; measurement pulses (0.2 or 1 ns FWHM) are alternated to wide pulses (20 ns FWHM) to obtain, in the receiving part, a proper trigger signal. The oscillator and the forming circuit are temperature controlled (T = 40 °C) to obtain very stable pulses. A 100 mV/50Ω output pulse allows the receiving oscilloscope to be triggered from the transmitter in the case of loop measurements.

Pulses of two different durations at the 50% of the peak (FWHM) can be selected (Fig. 3): 0.2 ns for measuring short and medium optical sections having high bandwidth (e.g. cable factory length) and 1 ns for measuring long links.

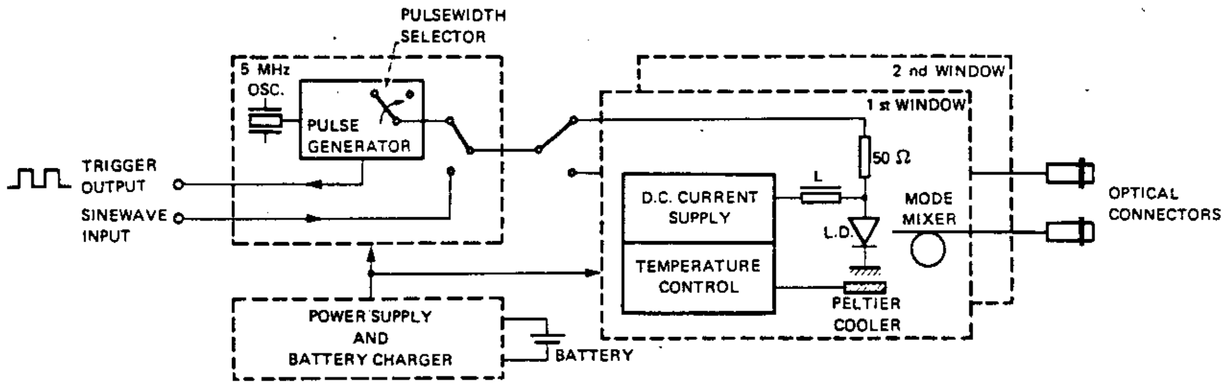


Fig. 1 - Schematic diagram of the transmitter unit.

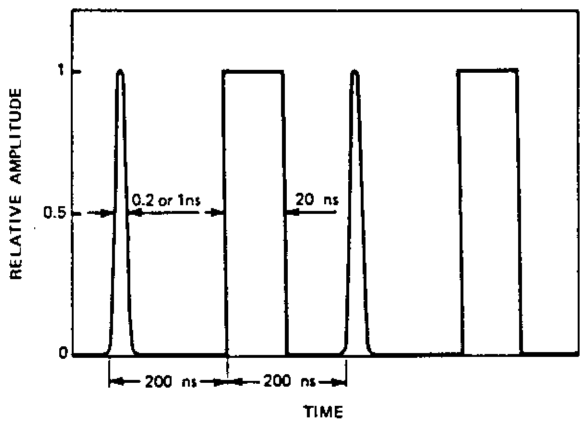


Fig. 2 - The optical pulse train injected from the transmitter unit into the fibre.

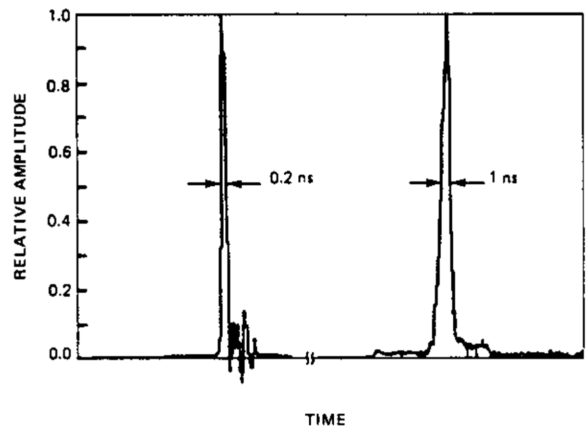


Fig. 3 - Shape of the two selectable test pulses (bandwidth limitation from receiver photodetectors and amplifier (OUT 1) is included).

The measured spectral width for the first window source is about 3 nm and 1.5 nm respectively for the 0.2 ns and 1 ns pulses; the 1300 nm source is somewhat wider than the 850 nm one but at this wavelength the chromatic dispersion is far less important.

The laser pigtail is connected, by a Springroove® splice to a mode-mixer obtained with three short pieces of 50 μm core fibres (step-graded-step index, 1 meter each) spliced together with Springroove® too. The mode-mixer terminates on a W.E.-Sirti optical connector.

The peak power injected into a 50 μm core fibre is about 1 mW. A 50Ω input port allows the laser to be driven by a sinusoidal signal for frequency domain measurement. The power source of the transmitter can be both external (220V A.C. line) or internal (12V/3Ah battery, assuring over four hours service).

3. Receiver unit

The receiver block diagram is shown in Fig. 4. The receiver is housed in a plug-in chassis for a commercial sampling oscilloscope mainframe.

The two optical inputs (850 nm and 1300 nm) are through W.E.-Sirti optical connectors. A miniature continuously variable optical attenuator has been designed and inserted between the inputs and the detectors. The use of an internal attenuator was decided despite the small loss (about 3 dB) introduced, as in the field use it is very handy not to have to employ an external attenuator. A Si APD is used as photodetector for the first window and a GaInAs PIN is used for the second window.

The second window PIN is connected to a first amplifier having 20 dB gain followed by two amplifiers (used for both the windows) having 20 dB each and bandwidth respectively of 1.5 GHz and 0.8 GHz. The output signal can be derived from any of two different points. The limiting in the bandwidth of the second amplifier reduces the noise of high loss fibres and gives no practical limitation in the field use.

A critical point in time domain field measurement is the trigger signal for the oscilloscope: for good results it must be not only higher than the trigger level (about 10 mV) but also noise free. In fact, it must be considered that the noise on the acquired signal can be reduced by an averaging process, while the trigger signal acts as it is and, if too

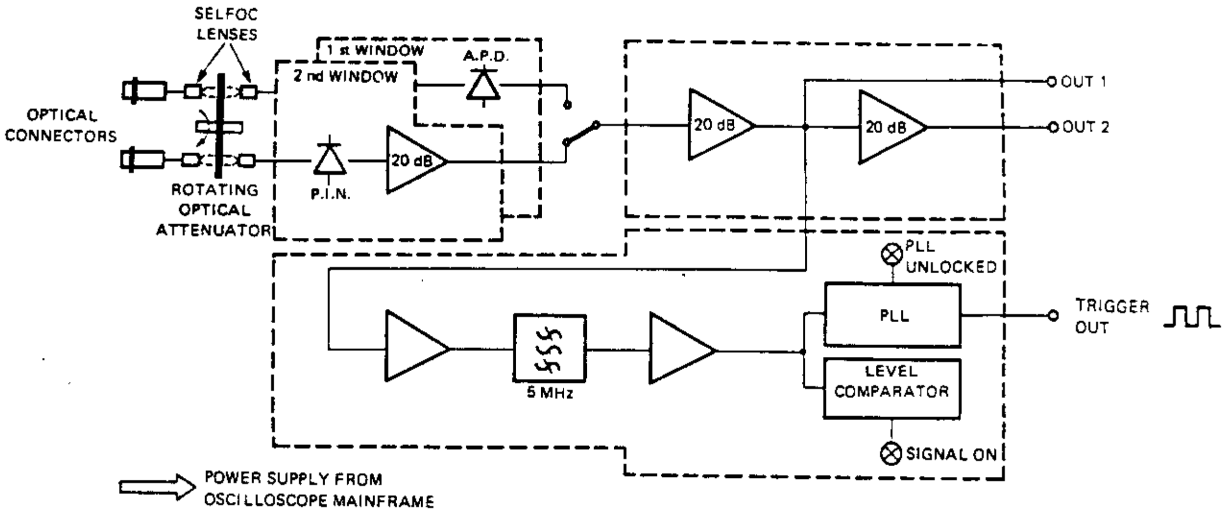


Fig. 4 - Schematic diagram of the receiver unit.

noisy induces a time jitter on the observed signal, spoiling the effect of the averaging.

To overcome the problem a circuit providing a 5 MHz square-wave locked on the received pulse train has been developed. This circuit includes a quartz bandpass filter, two amplifiers and a Phase-Locked-Loop (PLL) based on a quartz VCO. This circuit gives a good trigger signal on optical links having a 5 MHz loss not greater than about 30 dB.

To help the operator two LED's are provided on the receiver front panel. A green one indicates the presence of a suitable 5 MHz signal at the input of PLL, while a red one blows out when the PLL is get locked.

A desktop computer, to acquire from the oscilloscope and to process the received pulses, completes the time-domain measurements assembly.

For frequency-domain measurement the first output can be directly connected to a spectrum analyzer.

4. Operational limits

The useful range of the instrument is plotted in Fig. 5, for the first and second window, with reference to bandwidth and loss of the link under test; the three areas correspond to the usable ranges for each combination of the receiver outputs and the type of used pulse and gives a guidance for the operator in choosing the proper pulse and output; the area overlapping shows that the choice is not a critical point.

As in determining the usable ranges some arbitrariety exists, for the diagram in Fig. 5 reference was made to the use of a good sampling oscilloscope with numerical averaging function and the upper boundaries of the areas were determined as those giving on the oscilloscope a signal peak of at least 5mV and at least 50 times the r.m.s. noise, as reduced by the averaging on 1000 pulses. This assures on the processed signal an accuracy that is well sufficient for this type of measurement.

The total operational range is quite extensive: for istance a fibre having in the second window 0.9 dB/km loss and 1.8 GHz/km bandwidth can be measured for any length between 1 to 25 km; a fibre having in the first window 2.5 dB/km loss and 1 GHz/km bandwidth can be measured from about 1 km to 12 km (in both cases a concatenation factor γ = 0.5-0.7 has been considered).

To acquire the reference signals transmitter and receiver are connected via a few meters fibre.

5. Data acquisition and analysis

A four parts software package has been developed to acquire and process the data giving the frequency response of the fibre:

— a first part for data acquisition and storage on magnetic disk;

— a second part performs the Fast Fourier Transform (FFT) of the acquired signal, computes its ratio to the reference spectrum, and displays the loss and group delay behaviours of the fibre. Moreover the half peak durations of the reference and received pulses and the —1.5 dB, —3 dB and —6 dB frequencies on the fibre response are indicated;

— a third part allows the plotting of all the computed parameters;

— a final part computes:
 1) the Gaussian characteristic that best fits the fibre characteristic (different optimization criteria can be selected and alternatively a non-Gaussian fitting curve can be used) [3];
 2) the fibre response to a Gaussian pulse, and its autocorrelation function.

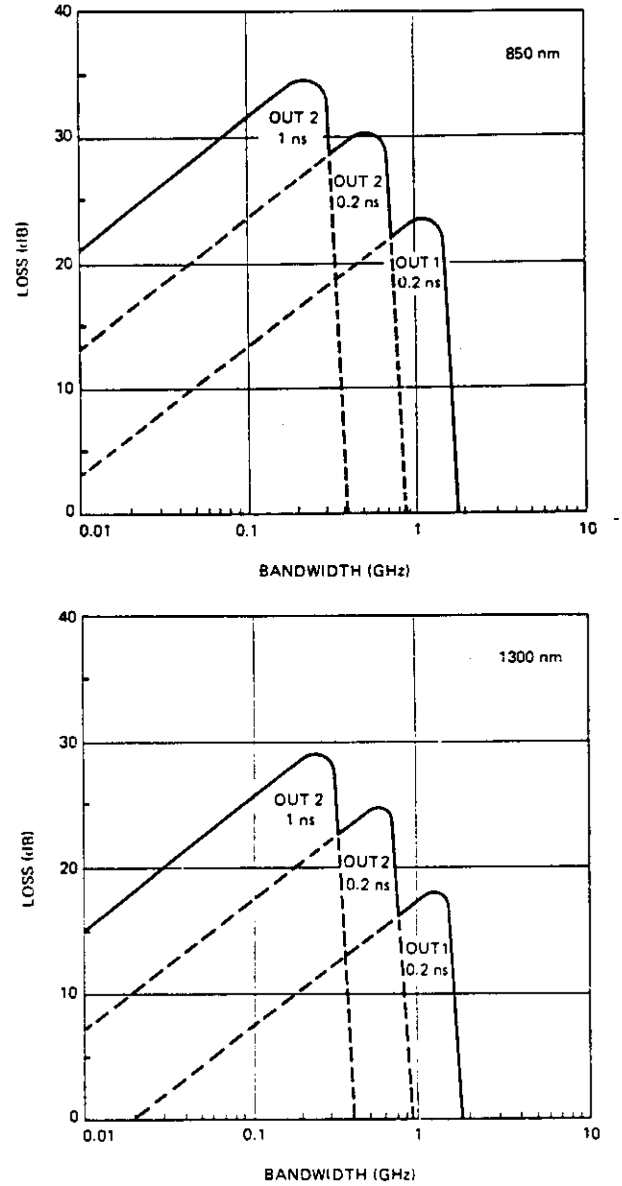


Fig. 5 - Working range for the bandwidth instrument in the 1st and in the 2nd window.

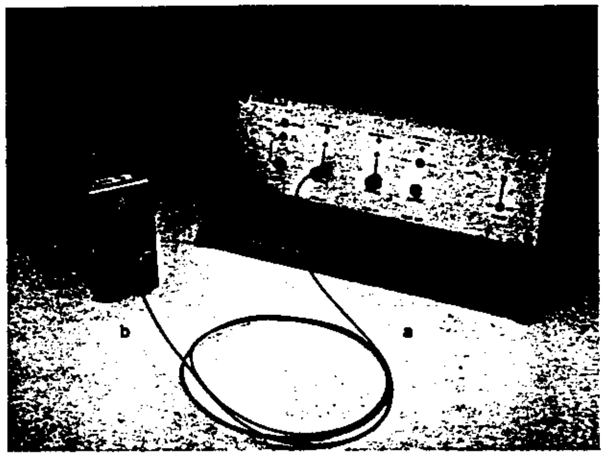


Fig. 6 - Photograph of the bandwidth instrument: a) transmitter; b) receiver.

6. Conclusion

The described instrument (Fig. 6) overcomes a few weaknesses of the previous pulsed laser time domain instruments, covering also the second window area and allowing an easy oscilloscope triggering through the special extraction circuit developed for the receiver.

The presence of ports suitable for sinusoidal signals increases the flexibility of the instrument.

The system has been successfully used in several field measurement where it gave no operational problems.

Acknowledgments

The authors are indebted to B. Santin and G. Sodaro for their contribution to this work.

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LABORATORY SESSION

MULTIMODE FIBER

TO OBTAIN THE FIXED (AND COMMERCIAL) BANDWIDTH PARAMETER OF A MULTIMODE FIBER (MULTIMODE BAND-WIDTH) TWO MEASUREMENT STEPS ARE NECESSARY:

STEP n. 1 : TO EVALUATE THE TOTAL BANDWIDTH (MULTIMODE + CHROMATIC) USING THE CSELT BANDWIDTH SET UP IN THE TIME DOMAIN TECHNIQUE

STEP n. 2 : TO OBTAIN THE CROMATIC DISPERSION CURVE (USING THE CSELT CHROMATIC SET UP) TO EVALUATE THE CHROMATIC DISPERSION INTRODUCED IN THE PREVIOUS MEASUREMENT BY THE SPECTRAL WIDTH OF THE LASER

STEP n. 1

WE PERFORM THE MEASUREMENT IN THE SECOND WINDOW USING A MULTIMODE FIBER ABOUT 1 Km LONG.
INPUT PULSES OF TWO DIFFERENT DURATION (AT THE 50% OF THE PEAK) CAN BE SELECTED, BUT THE NARROWEST PULSE MUST BE USED FOR THIS SHORT FIBER.

1) TO ACQUIRE THE OUTPUT PULSE

CONNECTING THE MULTIMODE FIBER BETWEEN TRANSMITTER AND RECEIVER WE CAN SEE, ON THE OSCILLOSCOPE SCREEN, THE BROADENED PULSE.
BEFORE TO ACQUIRE THIS PULSE WE MUST SELECT THE RIGHT TIME BASE FOR THE SAMPLING OSCILLOSCOPE TO OBTAIN :

- A GOOD EVALUATION OF THE PULSE WIDTH
- TO AVOID THE CUT OF THE PULSE TAIL
- A GOOD FREQUENCY STEP (1/TIME BASE) FOR THE BANDWIDTH CURVE

USING A D/A CONVERTER THE COMPUTER CONTROLS THE OSCILLOSCOPE SCANNING AND EVERY ACQUISITION POINT IS READ n TIMES (AVERAGING) USING AN A/D CONVERTER TO ACQUIRE THE PULSE TO THE COMPUTER.

2) TO ACQUIRE THE INPUT PULSE

CONNECTING A SHORT PIECE OF FIBER BETWEEN TRANS= METTER AND RECEIVER WE CAN SEE, ON THE OSCIL= LOSCOPE SCREEN, THE INPUT PULSE.

TO AVOID DISTORSION PROBLEMS IN THE RECEIVING UNIT THE OPTICAL ATTENUATOR MUST BE INSERT TO OBTAIN THE SAME POWER LEVEL, ON THE PHOTODETEC= TOR, MEASURED DURING THE PREVIOUS MEASUREMENT.

THE PULSE WIDTH IS LARGER THAN 0.2 nS (TRANS= MITTED OPTICAL PULSE WIDTH) BECAUSE THE PULSE PASSING THROUGH THE ELECTRICAL AMPLIFIER IS BROADENED BY THE LIMITED BANDWIDTH (ABOUT 1.5 GHz); THAT IS NOT A PROBLEM BECAUSE THIS EFFECT IS PRESENT BOTH FOR THE INPUT THAN FOR THE OUTPUT PULSE.

3) TO PROCESS THE INPUT AND THE OUTPUT PULSE

PROCESSING THE PULSES THE SOFTWARE (USING A FAST FOURIER TRANSFORMATION F.F.T.) CONVERTS THE MEASURED DATA IN THE TIME DOMAIN TO THE FREQUENCY DOMAIN.

AT THE END OF THE PROGRAM WE OBTAIN, FOR THE INPUT PULSE, A PLOT OF THE INPUT SPECTRUM INSTEAD, FOR THE OUTPUT PULSE, THE PLOT RE=

GARDS THE FIBER FREQUENCY CHARACTERISTIC.

THE −3 dB FREQUENCY POINT OF THE MEASURED AM- PLITUDE / FREQUENCY CHRACTERISTIC IS THE FIBER TOTAL BANDWIDTH (MULTIMODE + CHROMATIC DISPER- SION).

IF THE OBTAINED FREQUENCY CHRACTERISTIC HAS A GAUSSIAN BEHAVIOUR LIKE :

$$A = 3 \left(f / f_{3dB} \right)^2 \qquad [dB]$$

WE CAN SUPPOSE THAT THE MULTIMODE AND CHROMA- TIC DISPERSION ARE GAUSSIAN TOO, THEREFORE WE CAN USE :

$$B_T^{-2} = B_M^{-2} + B_C^{-2}$$

TO OBTAIN THE MULTIMODE BANDWIDTH (B_M) THAT IS THE ENDING POINT OF THE BANDWIDTH MEASUREMENTS ON MULTIMODE FIBERS.

FOR MULTIMODE FIBERS B_M IS THE COMMERCIAL DATA AND IT IS GIVEN FOR A ZERO SPECTRAL WIDTH SOUR- CE.

THE CHROMATIC BANDWIDTH CAN BE EVALUATED USING :

$$B_C = \frac{0.44}{c(\lambda) \cdot \Delta\lambda \cdot L \cdot 10^{-6}} \qquad [MHz]$$

WHERE $c(\lambda)$ IS THE CHROMATIC DISPERSION COEFFI-CIENT OF THE TESTED FIBER AT THE MEASURED WAVELENGTH , $\Delta\lambda$ THE SPECTRAL WIDTH OF THE LASER SOURCE USED DURING THE MEASUREMENT AND L THE LINK LENGTH.

THE SPECTRAL WIDTH OF THE SECOND WINDOW LASER EQUIPPED IN THE CSELT MEASURING SET UP IS ABOUT 4 nm.

TO EVALUATE THE CHROMATIC BANDWIDTH WE HAVE TO KNOW TO CHROMATIC DISPERSION COEFFICIENT $c(\lambda)$.

STEP n. 2

THE CSELT CHROMATIC DISPERSION SET UP WAS DEVELOPED FOR SINGLE-MODE FIBERS ; TO MAKE USE OF IT FOR MULTI-MODE FIBERS ALLOW ONLY AN INDICATIVE AND NO EXACT MEASUREMENT.

INFACT WITH MULTIMODE FIBERS ARE VERY IMPORTANT THE LAUNCHING CONDITIONS (OVERFILLED OR SMALL SPOT/ SMALL ANGLE) TO PERFORM A CORRECT MEASUREMENT ; IN THIS CASE THE LAUNCH IS REALIZED VIA A SINGLE-MODE FIBER AND THAT IS NOT THE RIGHT TECHNIQUE.

1) MONOCHROMATOR CALIBRATION

THIS PRELIMINARY STEP, FOR THE CHROMATIC DISPERSION MEASUREMENT, BEGINS SEARCHING THE STARTING POINT OF THE WAVELENGTH SCANNING MOTOR ; ALL THE NEXT MOTOR STEPS WILL BE PERFORM WITH REFERENCE TO THIS STARTING POINT.

AFTER SETTING THE OPTICAL ATTENUATOR AT THE POSITION OF MINIMUM ATTENUATION, THE WAVELENGTH SCANNING MOTOR RESEARCHES THE POSITION WHERE THE LASER POWER IS MAXMUM ($\lambda_c = 1294$ nm).

AT THE END OF THE PROCEDURE THE SOFTWARE RECORDS THIS MOTOR POSITION AND THEN ALL THE OTHER PROGRAMS WILL USE IT TO COMPUTE THE

MOTOR POSITION CORRESPONDING AT EVERY MEASU-
RED WAVELENGTH.

IN THE NEXT MEASUREMENTS AS SERVICE OPTICAL LINK WE WILL USE A SHORT PIECE OF FIBER TO SEND THE SINUSOIDAL MODULATING SIGNAL TO THE TRANSMITTER AND THE LED IN THE SECOND WINDOW AS SOURCE.

2) TO ACQUIRE THE FIBER PHASE DELAY
AFTER THE CONNECTION OF THE MULTIMODE FIBER THE SOFTWARE CAN START AND FOR EVERY MEASURED WAVELENGTH THE LEVEL AND THE PHASE ARE ACQUIRED WITH AN AVERAGING PROCESS.

3) TO ACQUIRE THE SYSTEM PHASE DELAY
THE SYSTEM PHASE DELAY IS OBTAINED REPLACING THE MULTIMODE FIBER WITH A SHORT PIECE OF FIBER. THIS MEASUREMENT IS NECESSARY BECAUSE THE WAVELENGTHS ARE NOT EMMITTED (BY THE LED) ALL AT THE SAME TIME.
FOR EVERY MEASURED WAVELENGTH (BEFORE TO ACQUIRE THE AVERAGED PHASE) THE OPTICA ATTENUATOR IS CONTROLLED TO OBTAIN THE SAME OPTICAL FIBER ON THE PHOTODETECTOR PREVIOUSLY MEASURED WITH THE MULTIMODE FIBER (TO

AVOID DISTORSION PROBLEMS).

4) TO PROCESS THE PHASE DELAYS TO OBTAIN THE FIBER CHROMATIC DISPERSION

THE SOFTWARE STARTS TRANSFORMING THE PHASE DATA TO DELAY DATA :

$$\tau(\lambda) = \frac{\phi(\lambda)}{2\pi f}$$

THE FIBER PROPAGATION DELAY BETWEEN THE WAVELENGTHS IS OBTAINED SUBTRAHEND FROM THE FIRST THE SECOND MEASUREMENT.

THE DELAY EXPERIMENTAL DATA WILL BE FITTED USING A SELLMEIER FUNCTION :

$$\tau(\lambda) = A\lambda^{-2} + B + C\lambda^{2}$$

THE FIRST DERIVATIVE OF THE FITTING FUNCTION IS THE CHROMATIC DISPERSION.

AS FINAL RESULTS WE HAVE A PLOT WITH THE FIBER PROPAGATION DELAY AND THE CHROMATIC DISPERSION CURVE.

AT THE END OF THE TWO MEASUREMENT STEPS WE HAVE ALL THE DATA TO EVALUATE THE MULTIMODE BANDWIDTH OF THE TESTED FIBER.

WE CAN USE THE FOLLOWING EXPRESSION TO COMPUTE THE CHROMATIC DISPERSION CONTRIBUTION INTRODUCED BY THE LASER SPECTRAL WIDTH USED TO EVALUATE THE FIBER TOTAL BANDWIDTH (STEP n. 1) :

$$B_C = \frac{0.44}{c(\lambda) \cdot \Delta\lambda \cdot L \cdot 10^{-6}} \qquad [MHz]$$

WHERE $\Delta\lambda$ IS THE SPECTRAL WIDTH (AT THE 50% OF THE PEAK) OF THE 2nd WINDOW LASER, L THE FIBER LENGTH AND THE CHROMATIC DISPERSION COEFFICIENT ($c(\lambda)$) MUST BE EVALUATED FOR THE LASER CENTRAL WAVELENGTH (1286 nm) :

TOTAL BANDWIDTH (B_T)	=		MHz
FIBER LENGTH	=	1	Km
$\Delta\lambda$ LASER	=	4	nm
c (1286 nm)	=		ps/nm·Km
CHROMATIC BANDWIDTH (B_C)	=		MHz

TO OBTAIN THE MULTIMODE BANDWIDTH :

$$B_M = \frac{1}{\sqrt{B_T^{-2} - B_C^{-2}}}$$

B_M IS THE SAME AS B_T FOR TWO REASONS:

a) THE MEASUREMENT IS IN THE SECOND WINDOW WHERE THE CHROMATIC DISPERSION CURVE IS NEAR ZERO

b) CORRECTLY WE USE NARROW SPECTRAL SOURCES IN THE SET UP TO HAVE A LOW CHROMATIC DISPERSION CONTRIBUTE

THE CHROMATIC DISPERSION IS LINEAR WITH LENGTH SO THERE ARE NO PROBLEMS TO PREDICT THE PULSE BROADENING OF A CONCATENATED LINK IF WE KNOW THE CHROMATIC DISPERSION CURVE OF EVERY FIBER.

FOR MULTIMODE DISPERSION IS IMPOSSIBLE TO PREDICT THE FINAL BROADENING OF A LINK ALSO IF ALL THE SINGLE MULTIMODE DISPERSION OF THE FIBERS ARE KNOWN.

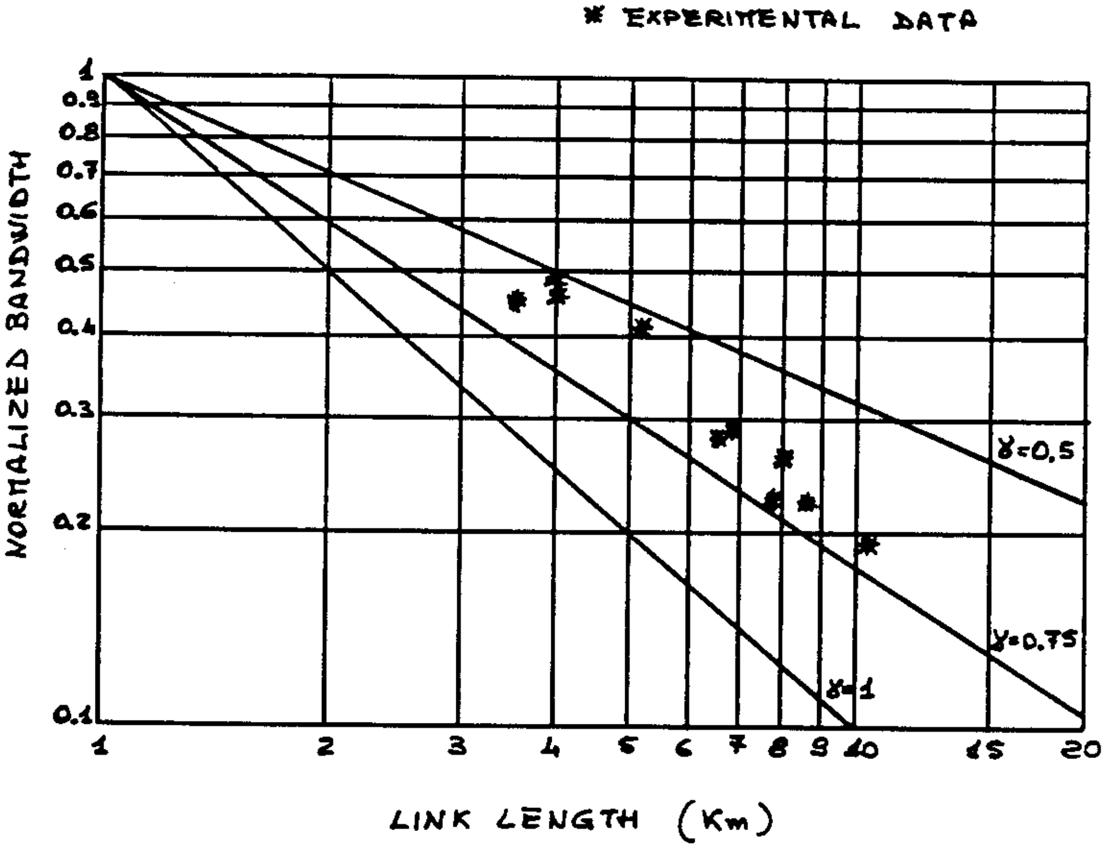
THE REASON IS THE TRANSFER OF OPTICAL POWER FROM ONE WAVEGUIDE MODE INTO ANOTHER (MODE MIXING) AT CONNECTORS, SPLICES AND IN THE FIBER ITSELF.

GENERALLY TO PREDICT THE MULTIMODE BANDWIDTH OF A LINK THE FOLLOWING EXPRESSION IS USED:

$$B = \left[\sum_{J=1}^{n} B_J^{-1/\gamma} \right]^{-\gamma}$$

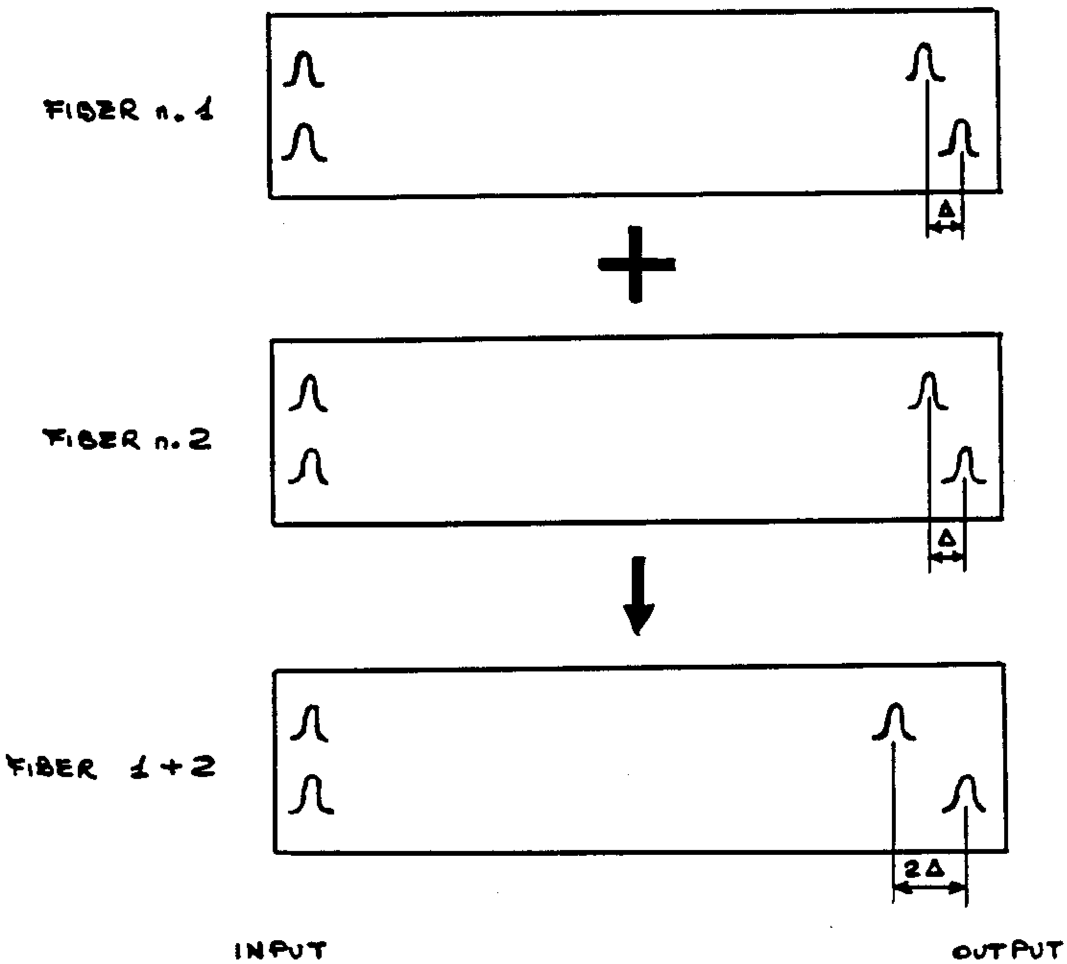
WHERE B_J IS THE MULTIMODE BANDWIDTH OF EVERYONE

OF n CONCATENATED FIBERS AND γ IS THE CONCATENATION FACTOR WITH A TYPICAL VALUE OF 0.75 VARYING BETWEEN 1 (LINEAR WITH LENGTH) AND 0.5 (LINEAR WITH THE SQUARE ROOT OF LENGTH).



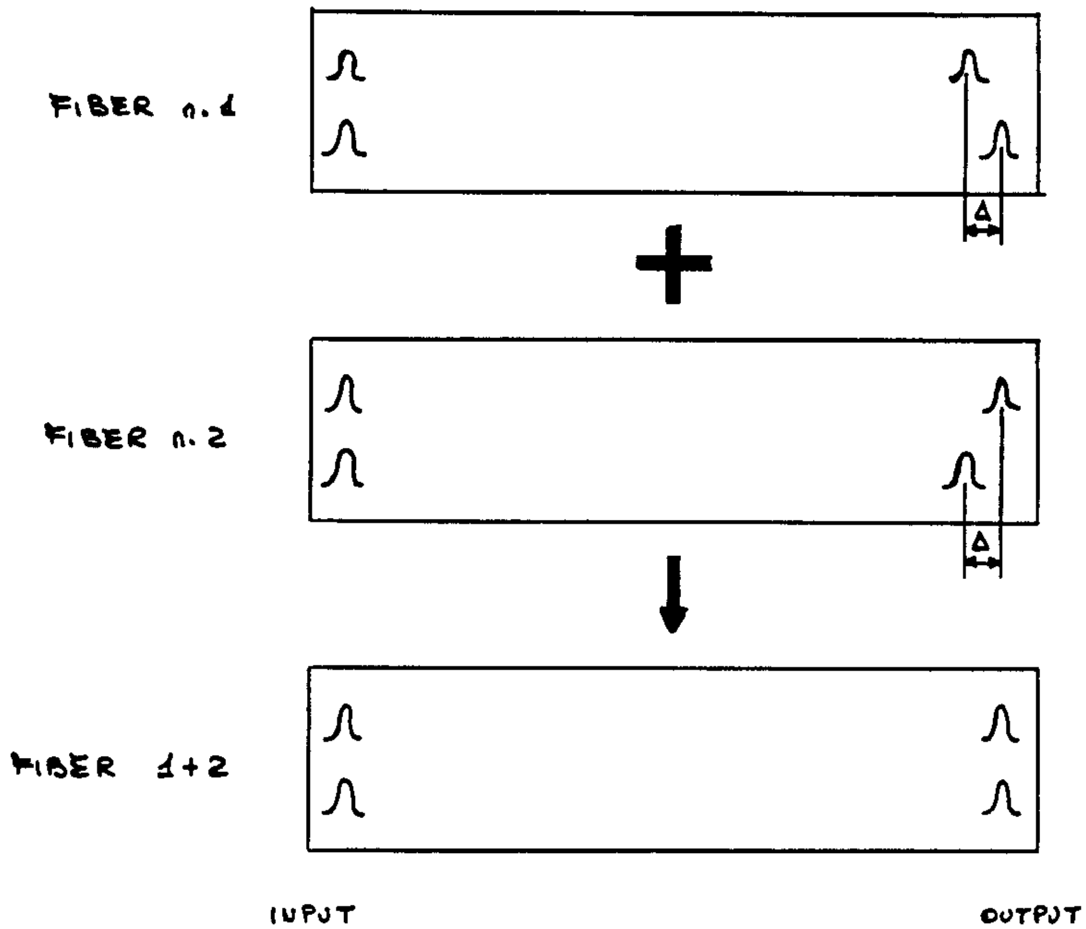
IS INTERESTING TO KNOW THAT ON SHORT LINK (TWO OR MAXIMUM THREE FIBERS CONNATENATED) THE MODE MIXING CAN LEAD TO OBTAIN A HIGHER MULTIMODE BANDWIDTH AS COMPARED TO A SINGLE FIBER.

POINT OUR ATTENTION ON THE FOLLOWING DELAY MODE DISTRIBUTION PICTURES :



IN THIS PICTURE THE TWO INPUT MODES TRAVEL ALONG THE FIBERS AND AT THE OUTPUT THE SAME DELAY MODE DISTRIBUTION IS PRESENT.

IF WE JOINT THE FIBERS AND AT THE SPLICING POINT MODE MIXING IS NOT PRESENT, THE FINAL DELAY BETWEEN MODES IS DOUBLE (LINEAR WITH LENGTH).



IN THIS PICTURE THE TWO INPUT MODES TRAVEL ALONG THE FIBERS AND AT THE OUTPUT THE OPPOSITE DELAY MODE DISTRIBUTION IS PRESENT.

IF WE JOINT THE FIBERS AND AT THE SPLICING POINT MODE MIXING IS NOT PRESENT, THE FINAL DELAY BETWEEN MODES IS ZERO AND THE MULTIMODE BANDWIDTH → ∞ (HIGHER AS COMPARED TO A SINGLE FIBER).

SINGLEMODE FIBER

WE PERFORM THE CHROMATIC DISPERSION MEASUREMENT USING A DISPERSION SHIFTED FIBER ABOUT 12.9 Km LONG (TWO FIBERS JOINTED TOGETHER).

FOR THIS MEASUREMENT WE REPEAT THE SAME MEASURING STEPS PREVIOUSLY PERFORMED FOR MULTIMODE FIBER (STEP n. 2) :

- MONOCHROMATOR CALIBRATION
- TO ACQUIRE THE FIBER PHASE DELAY
- TO ACQUIRE THE SYSTEM PHASE DELAY

AND THE DELAY EXPERIMENTAL DATA WILL BE FITTED USING A PARABOLIC FUNCTION :

$$\tau(\lambda) = A + B\lambda + C\lambda^2$$

AT THE END OF THE PHASE DELAYS PROCESSING WE OBTAIN A PLOT WHERE BESIDES THE CHROMATIC DISPERSION CURVE IS DRAWN A TABLE WITH THE MAXIMUM CHROMATIC DISPERSION COEFFICIENTS RECOMMENDED BY CCITT FOR DISPERSION SHIFTED FIBERS COMPARE WITH THE MEASURED DISPERSIONS:

WAVELENGTH (nm)	MAXIMUM CHROMATIC DISPERSION COEFFICIENT (ps / nm · Km)
1525 - 1575	3.5
1300	UNDER STUDY

FOR CONVENTIONAL FIBERS THE CCITT RECOMMANDATION IS THE FOLLOWING :

WAVELENGTH (nm)	MAXIMUM CHROMATIC DISPERSION COEFFICIENT (ps/nm · Km)
1285-1330	3.5
1270-1340	6
1550	20

WITHOUT MULTIMODE BANDWIDTH THE SINGLE MODE FIBERS REALIZE TELECOMMUNICATION OPTICAL LINKS WITH UNLIMITED BANDWIDTH AND THE ONLY BANDWIDTH PARAMETER WHICH CHARACTERIZE THEM IS THE CHROMATIC DISPERSION COEFFICIENT.

INFACT THE CHROMATIC BANDWIDTH IS A FIBER VARIABLE PARAMETER WHICH DEPENDS BY THE SOURCE SPECTRAL WIDTH EQUIPPED IN THE TELECOMMUNICATION TRANSMISSION SYSTEM.

A TELEPHONE COMPANY CAN LAY SINGLE MODE OPTICAL CABLES ALSO FOR SYSTEMS WITH LOW CAPACITY BECAUSE LATER ON IS POSSIBLE INCREASE THE LINKS CAPACITY CHANGING THE TELECOMMUNICATION APPARATUS ONLY.

USING THE RESULTS OF THE PREVIOUS MEASUREMENT WE CAN COMPUTE :

$$B_c = \frac{0.44}{c(\lambda) \cdot \Delta\lambda \cdot L \cdot 10^{-6}} \qquad [MHz]$$

FOR A LED ($\lambda_c = 1300 nm$) :

FIBER LENGTH	= 10 Km		
$\Delta\lambda$ LED	= 70 nm		
C (1300 nm ± 35 nm)	=	ps/nm·Km	(*)
CHROMATIC BANDWIDTH	=	MHz	

FOR A LASER ($\lambda_c = 1300 nm$) :

FIBER LENGTH	= 10 Km	
$\Delta\lambda$ LASER	= 4 nm	
C (1300 nm ± 2 nm)	=	ps/nm·Km
CHROMATIC BANDWIDTH	=	MHz

WE CAN SEE THAT ONLY WITH THE CHANGING OF TWO TERMINAL APPARATUS IS POSSIBLE TO INCREASE THE TRANSMISSION CAPACITY.

THE BEST SOLUTION FOR DISPERSION SHIFTED FIBERS IS TO USE THEM IN THE THIRD WINDOW WHERE THE MINIMUM OF ATTENUATION IS COUPLED WITH THE MAXIMUM OF BANDWIDTH PERFORMANCES :

(*) THE CHROMATIC DISPERSION COEFFICIENT IS EVALUATED FOR THE PESSIMISTIC CASE.

FOR A LED ($\lambda_c = 1550\,nm$) :

FIBER LENGTH	=	10 Km
$\Delta\lambda$ LED	=	100 nm
C (1550 nm ± 50 nm)	=	ps/nm·Km (*)
CHROMATIC BANDWIDTH	=	MHz

FOR A LASER ($\lambda_c = 1550\,nm$) :

FIBER LENGTH	=	10 Km
$\Delta\lambda$ LASER	=	4 nm
C (1550 nm ± 2 nm)	=	ps/nm·Km
CHROMATIC BANDWIDTH	=	GHz

BOTH THE PREVIOUS EXAMPLES USE ONE FIBER FOR EVERY TRANSMISSION DIRECTION ; FOR BIDIRECTIONAL TRANSMISSIONS ON THE SAME OPTICAL LINK , FLATTENED FIBERS CAN BE USED.

(*) THE CHROMATIC DISPERSION COEFFICIENT IS EVALUATED FOR THE PESSIMISTIC CASE .