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Intermodal Pulse Dispersion in Multimode Optical Fibres and Its Measurement with a Nanosecond Test Facility

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We discuss pulse dispersion in optical fibres and outline the various mechanisms which contribute towards it. The magnitude of each dispersion mechanism in different types of fibres is outlined and its effect on the information carrying capacity discussed. A Nanosecond Test Facility, for intermodal dispersion measurements is discussed in detail, together with the procedure for its operation. Some results obtained with this facility are illustrated.

Discutimos a dispersão de pulsos em fibras Óticas e destacamos os vários mecanismos que contribuem para isso. Foram discutidos ainda a magnitude de cada mecanismo de dispersão em diferentes tipos de fibras e seu efeito sobre a capacidade de transmitir informações. Um "Nanosecond Test Facility", ou arranjo experimental de resolução temporal de um nanosegundo, para medidas de dispersão intermodal foi discutido em detalhes, assim como o procedimento para sua operação. Alguns resultados obtidos com este arranjo estão ilustrados.

1. INTRODUCTION

There is a great interest in Brasil at the moment, towards development of fibre optical communications systems within the country. Graciosa[1] has outlined the various aims of the programme in Brasil and the work being carried out towards its fulfillment. For a brief history of optical fibres and the various components of a system using these, the reader is referred to the articles by Kao[2] and Maurer[3]. Optical fibres are being pulled[4] at the "Padre Roberto Landell de Moura" Research and Development Centre of Telebrâs and we have been carrying out measurements[5,6,7] on these to assess them experimentally.

Two fundamental measurements to be carried out after pulling a fibre are its spectral attenuation and pulse dispersion[8]. Attenustion of the fibre limits the maximum spacing between repeaters in a communication link and dispersion limits its bandwidth or the maximum information capacity. Dispersion is defined as the broadening that occurs in a short, subnanosecond light pulse after propagation in the optical fibre. By measuring this broadening (τ) we can conservatively determine the maximum pulse bit rate (B) that we can transmit through a particular fibre by using $B = (2\tau)^{-1}$ for unity mark/space ratio. Hence the great importance of such measurements and the effect of diverse parameters on the broadening for optimum system design. The aim of this paper is to discuss pulse dispersion in depth and also its measurement with a Nanosecond Test Facility. The paper is divided as follows: section 2 discusses the pulse dispersion problem in considerable depth, including the various mechanisms that contribute towards it and their relative magnitudes in different types of fibres; section 3 contains details of the Nanosecond Test Facility including the choice of the various components and possible alternatives, the procedure for measuring intermodal pulse dispersion and the precautions necessary, and some examples of the results obtained. We conclude in Section 4 with discussion and conclusion.

2. THE PULSE DISPERSION PROBLEM

Pulse code modulation (PCM) is being incresingly used in communication systems, and since lasers can be mode-locked[9] readily to give short optical pulses, pulse dispersion in an optical fibre, and hence its bandwidth, can be directly and conveniently determined by launching a short optical pulse into it and observing the broadening that occurs in the pulse profile. This technique also shows the change in the pulse profile, of importance to the systems designer. If τ_1 is the full-width at half-maximum intensity points of the input pulse and τ_2 of the output pulse, then the pulse dispersion ($\Delta\tau$), assuming Gaussian pulse shapes, is given by $\Delta\tau = (\tau_2^2 - \tau_1^2)^{1/2}$.

2.1. Types of Optical Fibres

There are three basic types of fibres and the pulse dispersion in each is markedly different. These are:

(i) the step-index multimode fibre

(ii) the graded-index multimode fibre

(iii) the single-mode or monomode fibre.

The step-index multimode fibre is shown in fig. 1(a) together with its refractive index profile. The fibre core diameter (d_1) is much greater than the wavelength of light, λ, (20-50 μm); has uniform refractive index distribution n_1. The core is surrounded by a relatively thin cladding (2-20 μm) of refractive index n_2, where n_1 is much greater than n_2. Since $d_1 >> \lambda$ and $n_1 >> n_2$, the multimode fibre supports many hundreds of modes (N_1), given by $N_1 = V^2/2$ where V, a normalised frequency parameter, is given by $V = (\pi d_1/\lambda)(n_1^2 - n_2^2)^{1/2}$.

The graded-index multimode fibre is shown in fig. 1(b). As the

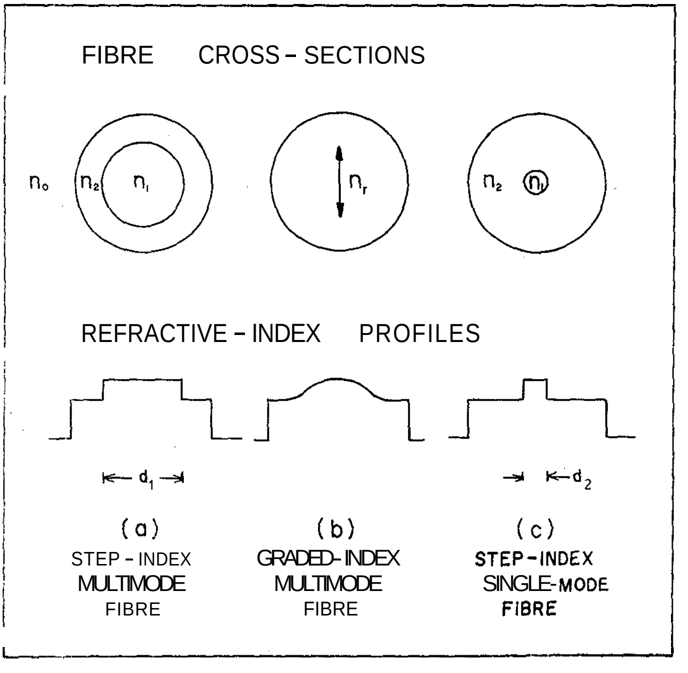

Fig.1 - Three basic fibre types, their cross-sections and the refractive -index profiles.

name implies, the refractive index profile of the core is graded i.e. it decreases radially from the centre of the fibre axis as

$$n_r = n_1 \left[1 - \Delta \left(\frac{r}{a}\right)^{\alpha}\right], \quad 0 \leq r \leq a$$

$$n_r = n_1 \left[1 - \Delta\right] \quad , \quad r > a$$

where a is the core radius, A is the relative refractive index difference given by $n_2 = n_1$ (1 - A), and a is an exponent which rises to infinity for a conventional step-index multimode fibre. For a value of a ≃ 2, the number of guided modes (N_2) in a graded-index fibre is only half the modes in a step-index fibre with the same values of A and core diameter.

The single-mode fibre shown in fig. 1(c), has core diameter (d_2) comparable to h and n_1 is just greater than n_2. The fibre supports only one spatial propagation mode and for this condition at a particular h, we must have V < 2.405; as before V is given by $(\pi d_2/\lambda)(n_1^2 - n_2^2)^{1/2}$.

2.2. Mechanisms Contributing to Pulse Dispersion

A short optical pulse broadens after propagation in an optical fibre due to the following mechanisms:

(a) *Intermodal dispersion* (r_g) is caused by the differences in the group velocities of the various mdes propagating in the fibre. Various other terms have also been used to refer to intermodal dispersion, such as modal dispersion, waveguide dispersion, multi-path dispersion, multimode dispersion and mnochromatic dispersion. τ_g is completely dominant in a multimode step-index fibre as N_1 is large, and the other dispersive mechanisms, as discussed below, can be neglected. By designing a graded-index fibre, $N_2 = (1/2)\, N_1$, and hence r_g can be reduced drastically; it is eliminated completely in a single-mode fibre as $N_1 = 1$. The discussion and measurement of τ_g in multimode fibres is the subject of this paper.

(b) *Intramodal dispersion* (τ_m) is due to the wavelength dependente of the fibre core refractive index, causing velocity differences among the spectral components of the light source used. Two other terms have also been used to refer to r_m, namely, material dispersion and chromatic dispersion. r_m is negligible compared to r_g in step-index multimode fibres even if a light emitting diode (LED) with 40nm spectral width, is used as the light source. With optimally designed graded-index multimode fibres τ_g can be ~ 1 nsec/km and hence with LED excitation, τ_m can be greater than τ_g for $\lambda < 1$ µm, as shown by Dawson[10]. Further τ_m is a strong function of λ, varying inversely and τ_m can be zero in the region of 1.3 µm.

(c) *Mode Dispersion* (τ_m) of a particular propagating mode caused by the frequency dependence of the propagating constant of that mode. As the magnitude of τ_m is very small, it will only be important in single-mode fibres operated near the zero material dispersion region.

(d) *Profile Dispersion* (τ_p) is caused by the variation, with wavelength, of the relative refractive-index difference between core and cladding. τ_p will be important only in graded-index fibres, at a given wavelength, so that τ_g can be minimised. We have previously shown[8,11] that τ_p was negligible compared to τ_g with measurements carried out at three wavelsngths, (694, 782, 871 nm) but the results cannot be generalised: the relative refractive index difference between core and cladding as a function of wavelength can be markedly different as many different materials have been used for the core of optical fibres.

2.3. Intermodal Dispersion in Multimode Fibres: Rays and Modes

Each propagation mode of the fibre has its own characteristic mode pattern, that emerges from the fibre. In figure 2 we illustrate the mode patterns of the fundamental HE_{11} mode of the single-mode fibre, and a few other higher order modes. By selecting a particular V value of the fibre, as defined above, the fibre can propagate only one mode or a few modes. In this case, it is important to carry out an analysis involving each mode and hence the total effect after propagation in the fibre. But in a step-index multimode fibre, the number of modes in inconveniently large. As an example, we take the liquid-core fibre[11] with $n_1 = 1.551$, $n_2 = 1.485$ at $\lambda = 0.633$ µm, and a core diameter $d_1 = 57$ µm. Then the normalised frequency parameter $V = (\pi d_1/\lambda)\,(n_1^2 - n_2^2)^{1/2} = 125$, and the number of guided modes is ~ 7.800. Hence it is simpler and more convenient to consider the various modes as light rays in terms of the simple geo-

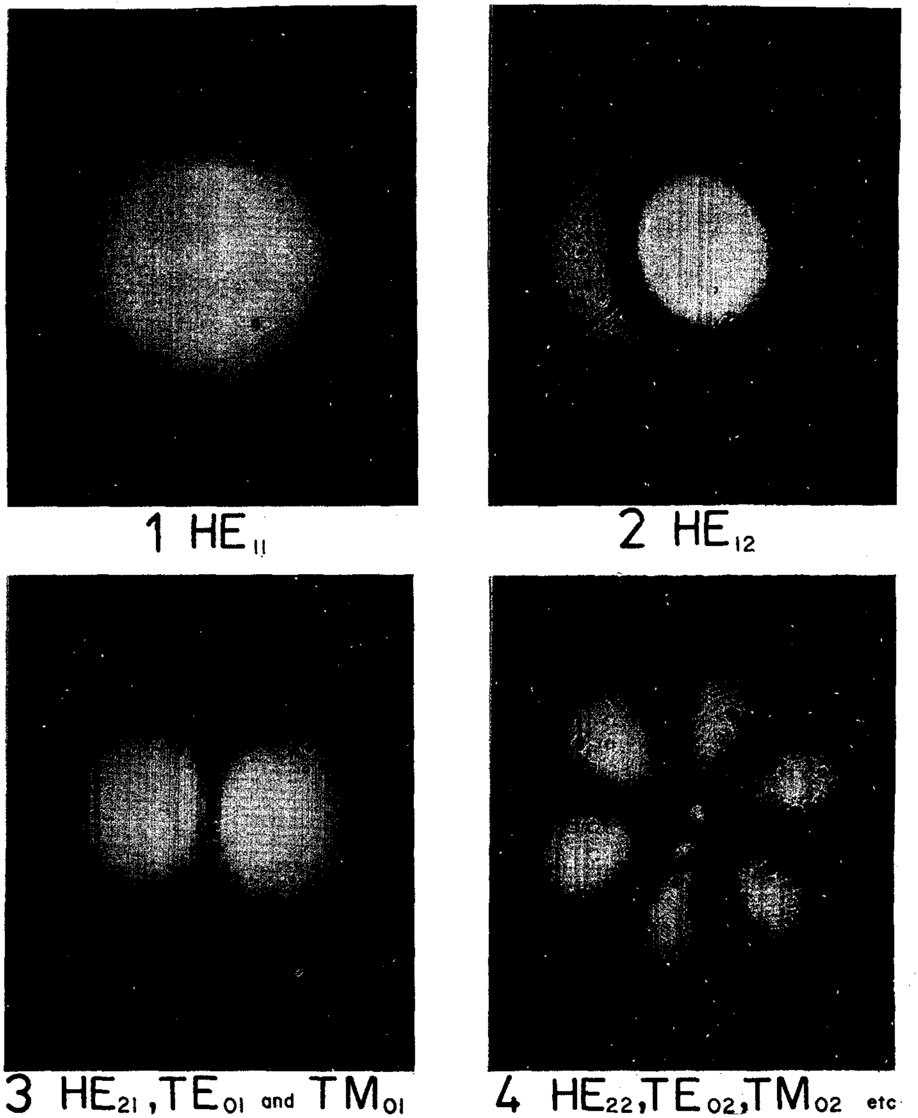

Fig.2 - Mode patterns of optical fibre

metrical optical model, giving each ray its propagation angle (ϕ) with respect to the fibre axis, and an amplitude, depending on the launching conditions. Such a Ray Propagation Model has been used[8] very successfully to predict the relative propagation delay and pulse dispersion in such multimode fibres. The maximum angle (ϕ_c) of a ray that the fibre accepts determines its numerical aperature, which is given by $\sin \phi_c = (n_1^2 - n_2^2)^{1/2}$,

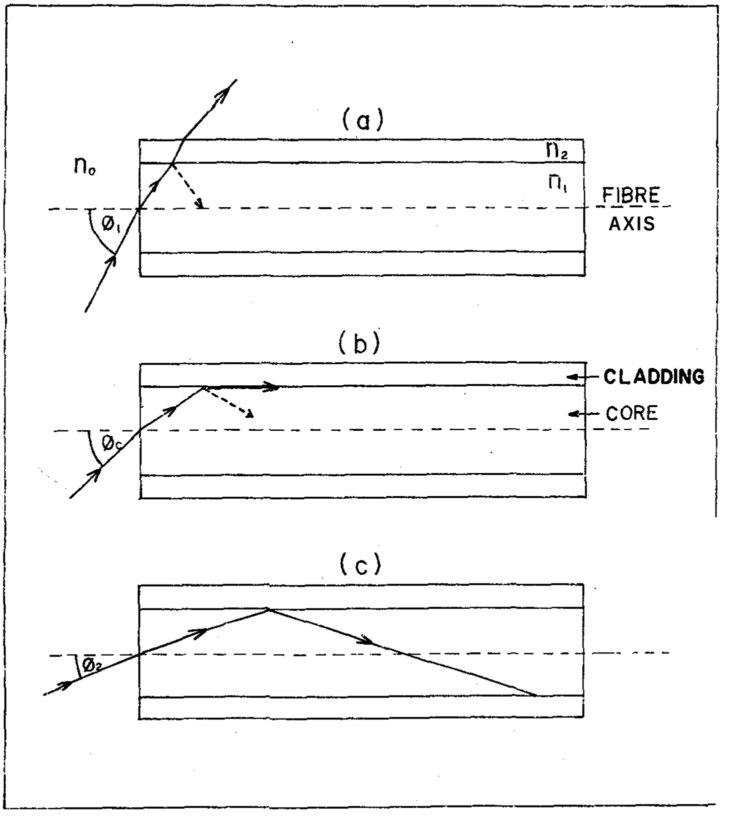

Fig.3 - Various light rays incident on a step-index multimode fibre: (a) $\phi_1 > \phi_c$ - ray not guided in the fibre; does not suffer total internal reflection. (b) ϕ_c is maximum ray angle accepted by fibre. (c) $\phi_2 \lesssim \phi_c$ - all rays guided in the fibre.

as shown in fig. 3(b). If $\phi_1 > \phi_c$ as in fig. 3(a), the ray does not suffer total internal reflection at the core-cladding interface and hence is not guided within the fibre. Only for $\phi_2 \lesssim \phi_c$, as in figures 3(b) and (c), the fibre will guide the light rays within its core. Therefore, intermodal dispersion can be understood easily by envisaging various rays propagating in the fibre having angles $0 < \phi < \phi_c$. It can be shown that the relative propagation delay (Δt) of a ray launched at an angle θ with respect to the fibre axis in air, is given by

$$\Delta t = \frac{n_1 L}{c}\left\{ \sec\left[\sin^{-1}\left(\frac{\sin\theta}{n_1}\right)\right] - 1\right\}$$

where L is the fibre length and n_1 is the core refractive index. As 8 increases, so does Δt and if a short light pulse is launched into all the rays which can propagate at different angles in the core, the output pulse will be broadened. Intermodal dispersion is completely dominant in step-index multimode fibres and is of the order of 30 ns/ km for every per cent of indexdifference between coreand cladding. In a graded-index multimode fibre, τ_g can be reduced considerably only if launching is carried out correctly, by matching the launching spot-size to the characteristic spot-size of the fibre; with mismatched launching conditions[12], τ_g becomes large, comparable to that obtained with step-index multimode fibres. In figure 4, we illustrate the path of light rays in the various fibre types

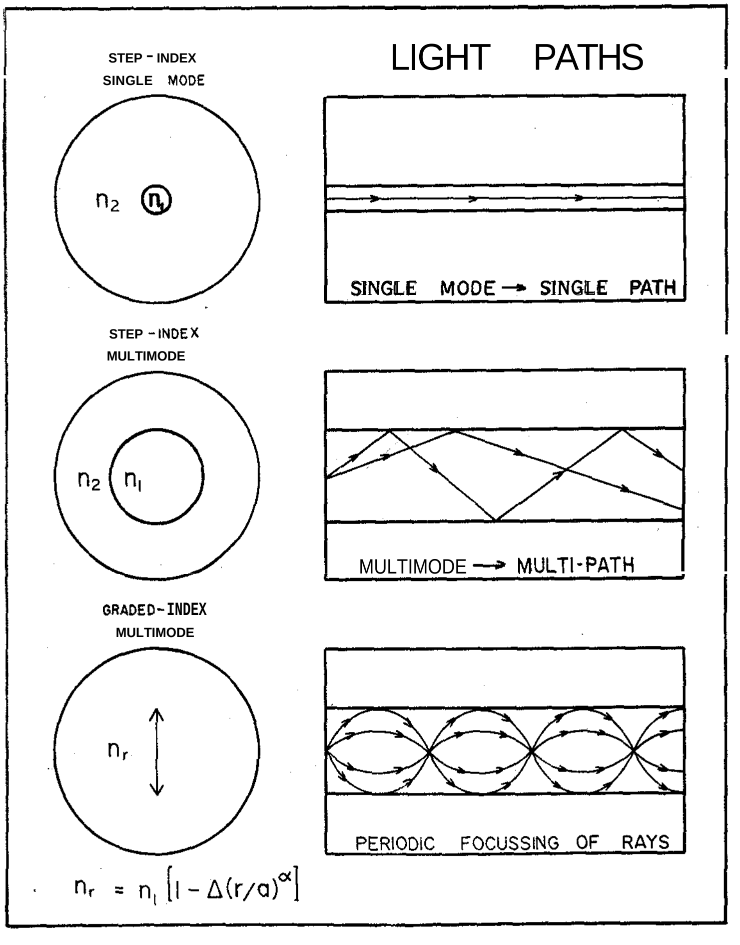

Fig.4 - Fibre types and the paths of the light rays within these fibres.

3. A NANOSECOND TEST FACILITY

The problem of measuring intermodal pulse dispersion in a multimode fibre falls into these categories, (i) to select a suitable optical oscillator which produces optical pulses, (ii) to launch the light efficiently into the fibre, (iii) to detect the optical pulses, that emerge frorn the fibre, with a photodetector, or other suitable system, (iv) to display the input and output pulses to the fibre and to record these for measurement and interpretation of intermodal dispersion.

To observe a clear broadening, the response of the measuring system has to be much smaller than the intermodal dispersion of the fibre. To malte the measurement system fairly versatile, it should be able to measure intermodal dispersions of ~ 1 ns, which would be observed in long lengths of graded-index fibres and short lenghts of step-index fibres. Hence the combined response of the input optical pulse, the photodetector and the oscilloscope has to be much less than one nanosecond, i. e. each of these components has to have a response of the order of a few hundred picoseconds.

3.1. Production of Subnanosecond Optical Pulses

We used a semlconductor laser as the source of the optical pulses for the following reasons: (i) large pulse peak powers can be easily obtained, (ii) the output wavelength of semiconductor lasers can be varied between 0.8 μm and 1.5 μm by suitable choice of the materials; and this is the region of interest in optical fibres since they have minimum attenuation and minimum dispersion within this region, (iii) semiconductor lasers can be easily modulated to produce optical pulses having durationsof a few hundred picoseconds, (iv) systems will use these devices due to their compactness and easy modulation; hence measurement in the laboratory with semiconductor devices determines the characteristics of the fibre accurately, as would be encountered in field conditions. This is particularly important since the output spatial characteristics of semiconductor lasers are completely different to other gas or solid- state lasers, e.g. He-Ne and ruby lasers, which also have been used for dispersion measurements[8].

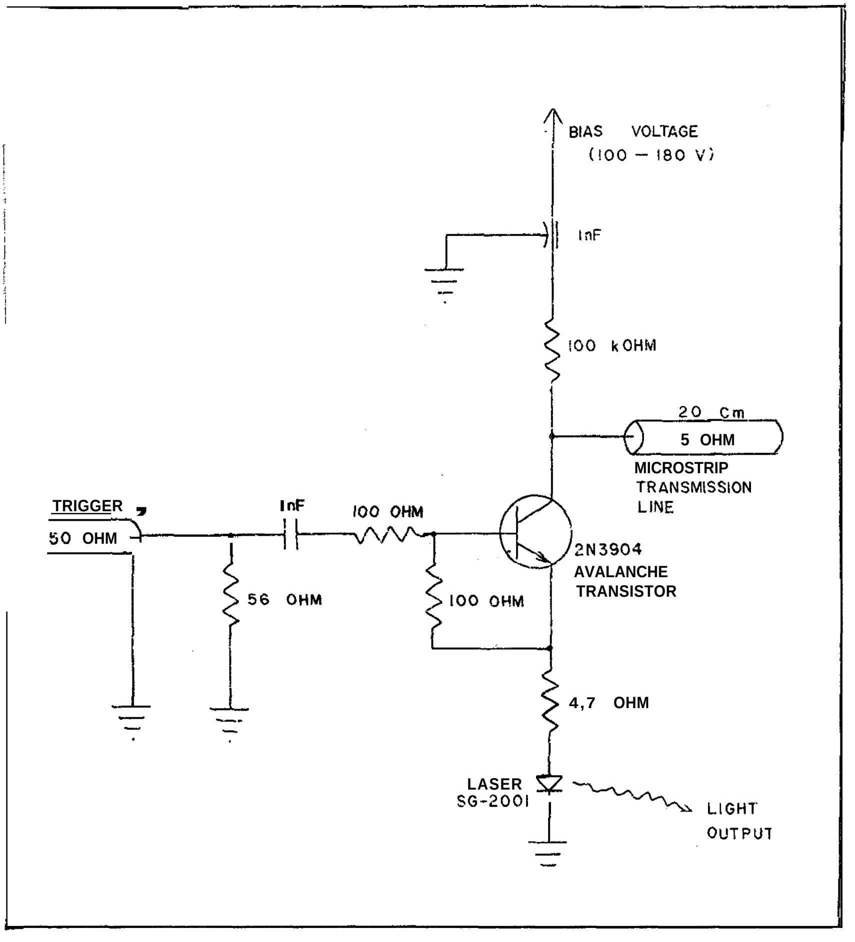

Fig.5 - Circuit used to generate subnanosecond pulses from a semiconductor laser (after Andrews[13]).

The electronic circuit used for the generation of subnanosecond pulses is illustrated in figure 5, first developed by Andrews[13]. The cost of this laser pulser is mostly due to the cost of the laser, We have used various lasers, including RCA SG 2001, emitting at 904 nm, LD-60 series lasers manufactured by Laser Diode Laboratcries and emitting at wavelengths between 800-900 nm. The bias voltage to the circuit, for different lasers, was adjusted to give the principal pulse and the minimum of subsidiary pulses. All other precautions necessary are mentioned in detail in the paper by Andrews[13].

3.2. Launching and Detection Optics

The launching and detection optics have to be designed carefully bearing in mind that the semiconductor laser emits in the near infrared. This is fairly important for measurements to be done rapidly and with ease. With a visible cw laser, such as the He-Ne laser, measurements can be carried out easily without any special optical components.

In figure 6(a) is the schematic arrangement of the launching arrangement and the photograph, figure 6(b), show the components used. Since the laser (L) emits light with a large divergence angle, microscope objective M_1, magnification x45 with a numerical aperature of 0.65, is used to collect all the light and collimate it into a parallel beam. This parallel beam passes through a tetravar intermediate unit (T), which houses a beam-splitter (B.S.). The light is focussed into the fibre by microscope objective M_2, which can be changed to vary the launch numerical aperature. The fibre is held in position by a vacuum chuck[14] (V.C.). To the tetravar intermediate unit is attached an illuminator (I), an inclined monocular eye-piece unit (M.T.) and a microscope infrared viewer, (I.V) manufactured by Electrophysics Corporation. This arrangement is necessary (i) to position the laser at the focal point of microscope objective M_1 end is done by rotating the beam-splitter to position P_2 and viewing through the infrared viewer; (ii) to focus the light into the fibre. This is done by rotating the beam-splitter to position P_1. The fibre end is placed at the focal point of the microscope objective M_2, and then is further adjusted so that the Fresnel reflection of the laser spot from the fibre end can be observed, again through the infrared viewer. Fine adjustment of the fibre position enables the laser focussed spot to be positioned in the middle of the fibre core.

The light emerging from the fibre end is observed with a detection arrangement, exactly similar to the launching arrangement, and shown in fig. 7. Focussing of the output light into the photodetector (D_2) is done similarly by observing the Fresnel reflection from the detector. Microscope objective M_3 (x20, N.A. = 0.54) has a numerical aperature greater than that of the fibre to capture all the light rays emerging from the fibre. Microscope objective M_4 has a magnification of x10 and ensures that the focussed spot diameter is less than the diameter of

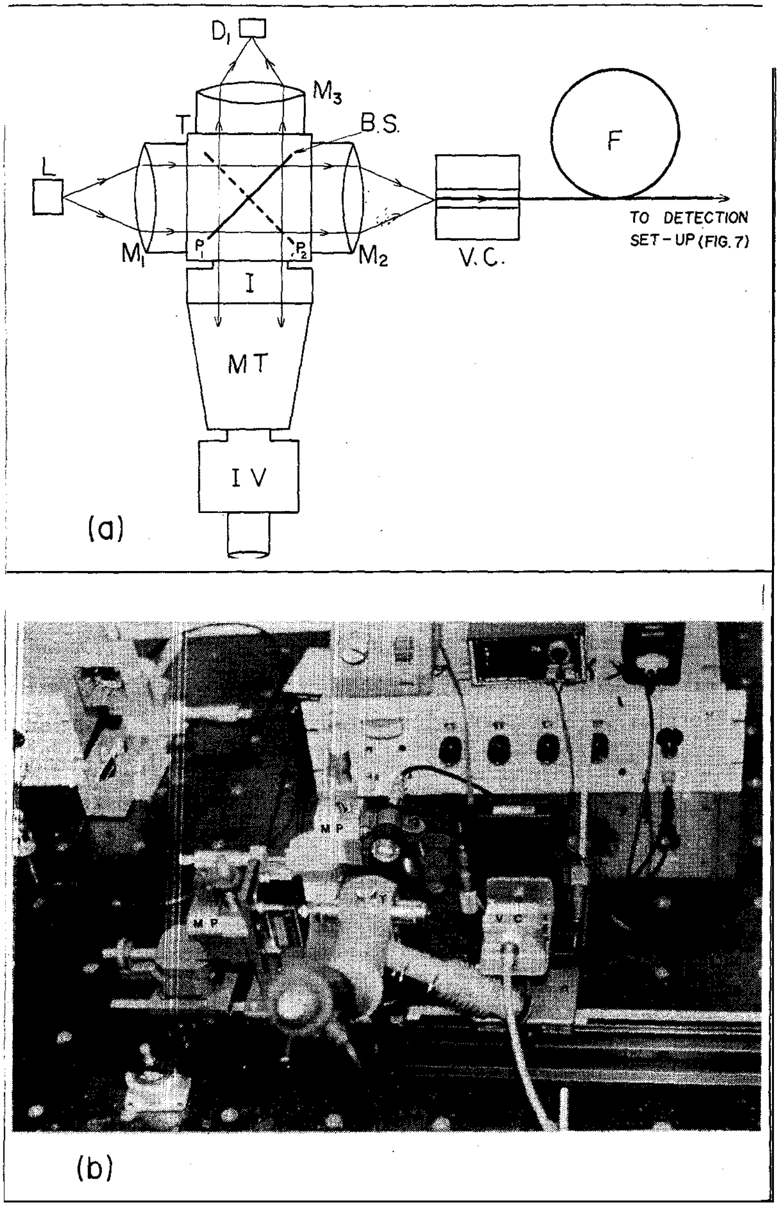

Fig.6 - (a) Schematic diagram of the launching arrangemnt. (b) Photograph of the equipment used. L - semiconductor laser; M_1 - microscope objective (x45); M_2 - microscope objective (x10) or other coupling lens; M_3 - coupling lens; D_1 - silicon avalanche photodetector; T - Ealing Tetravar Intermediate Unit; B.S. - beam-splitter; P_1, P_2 - two positions of the beam-splitter; I - Illuminator unit; H.T. - inclined monocular eye-piece unit; I.V. - microscope infrared viewer; F - fibre under test; M.P - micro-positioners; V.C. - vacuum chuck.

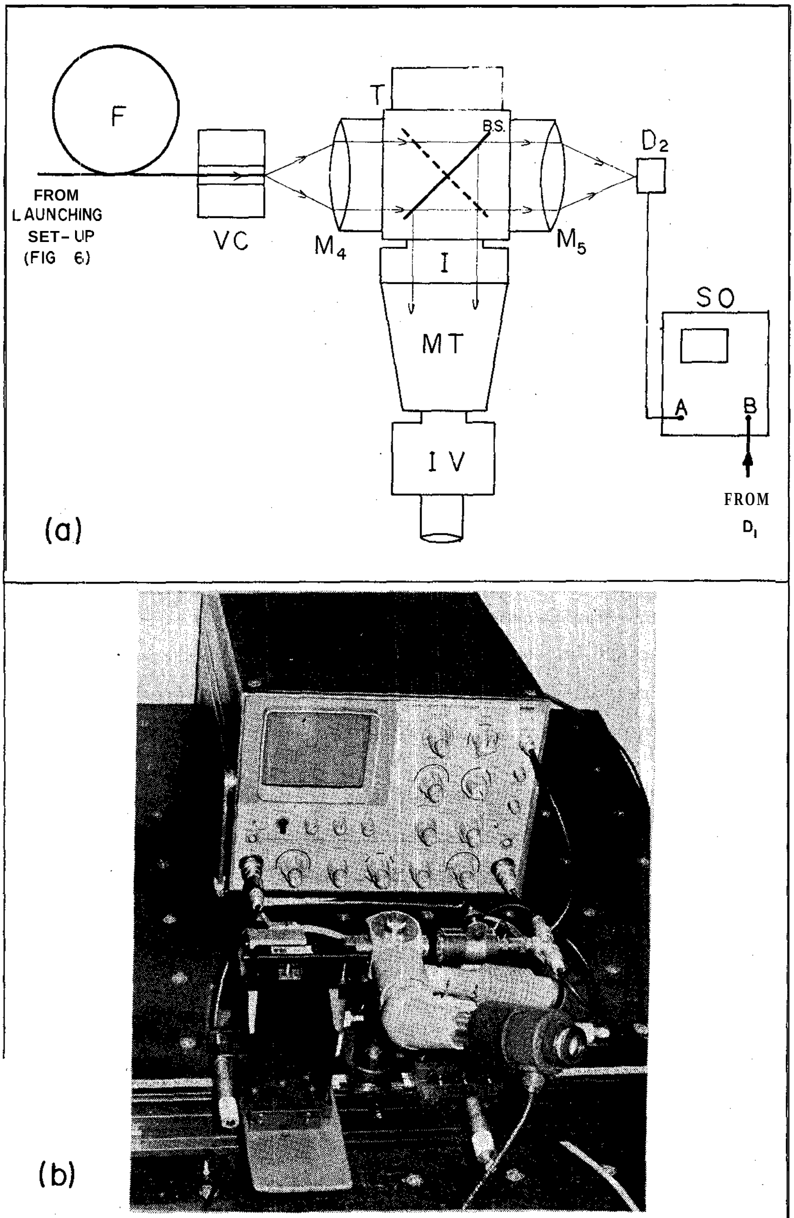

Fig.7 - (a) Schematic diagram of the detection arrangement. (b) photograph of the equipment used. M_3 - Microscope objective (x20); M_4 - microscope objective (x10); S.O. - Phillips Sampling Oscilloscope, Model PM 3400 (other components are similar to those described in fig. 6).

the active area of the photodetector. If this is not done, the dispersion measured will be less than its true value, caused by eliminating light which travelled at the higher angles; in other words, filtering of higher order modes.

3.3. Detectian and Display of Output Pulses

The requirements of the photodetector are (i) high sensitivity so that large actenuatioris in the fibre can be tolerated and hence measurements in long lengths are possible, (ii) high time resolution so that even sinall magnitudes of dispersion may be detected, specially in long lengths of graded-index fibre. Presently silicon avalanche diodes fulfill this requirement very aaequately and we used various types manufactured by EMI, RCA and other companies. All had response of less than a few hundred picoseconds and were very adequate for our measurements. Recently, an ultra-high-speed photodiode, Model 403 B, manufactured by Spectra-Physics, has become available, and has a rise- and fall-time of -50 psec. Although it is not of the avalanche type, it can still be used for dispersion measurements as fibre loss can be extremely low (<1 dB/km) and hence the input pulse wouldnoc suffer much attenuation.

The display of the pulses has to be done on sampling oscilloscope as real-time oscilloscopes donot have the speed necessary. We have used a Phillips Sampling Oscilloscope, Model PM 3400, having a rise-time of 200 ps. If a much faster response is required, a Tektronix Sampling Oscilloscope with 25 psec risetime can be used, consisting of 7904 mainframe, two 7S11 Sampling Units, 7T11 Sampling Sweep and two S-4 Sampling heads. Permanent records of the observed pulses can be made either by photographing the pulses from the oscilloscope or feeding a suitable output from it to an X-Y recorder.

3.4. Procedure for Measuring Dispersion and Results Obtained

The fibres ends are first prepared, to have a mirror finish, by using a fibre breaking machine constructed on the principles first reported by Gloge *et al.*[15] The mirror finish is checked by observing the ends with a microscope. This is important to achieve a high launching efficiency and to launch accurately with a known numerical aperature. The fibre ends are then placed in the vacuum chucks and held firmly in position. Thé laser L is switched on and with the beam-splitter of fig. 6 in the position P_2, it is placed at the focal point of objective M_1. The beam-splitter is then rotated to position P_1 and the light focussed onto cletector D_1 with a coupling lens M_3. The output from the detector is fed to the sampling oscilloscope. By observing the trace on the oscilloscope, the input profile is optimised by adjusting the supply voltage to the laser pulser. Fig. 8(a) shows one example of the result obtained. The light is launched into the fibre by observing the Fresnel

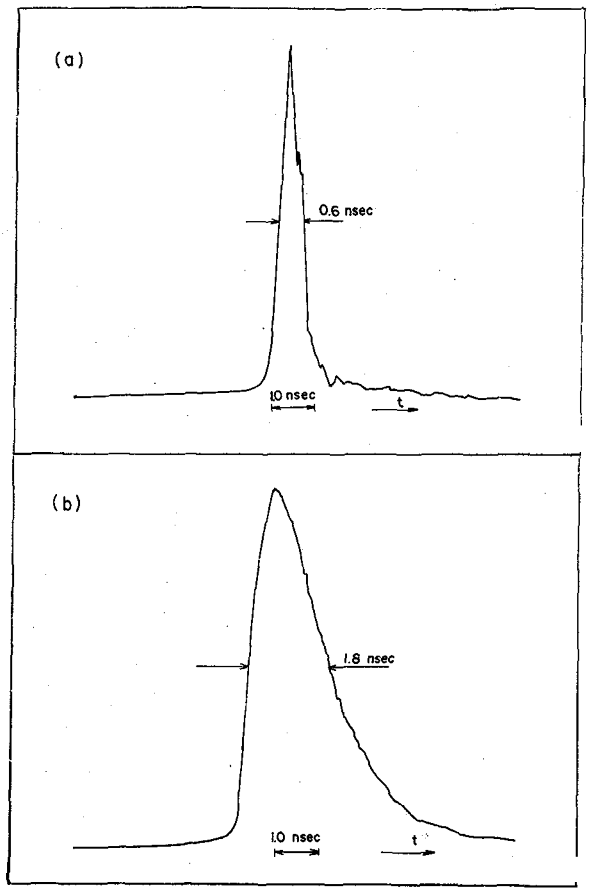

Fig.8 - An example of the results obtained with the Nanosecond Test Facility: (a) Input pulse launched into fibre. (b) Output pulse after 105 m of Telebrās fibre 79. Intermodal pulse dispersion is 1.7 nsec, after deconvolution of input pulse.

reflectior from the end of the fibre, as already discussed in section 3.2. The output from detector D2 is also fed to the sampling oscilloscope. In fig. 8(b) is the output pulse observed after propagation in 105 m of Telebrás fibre 79. After deconvolution of the input pulse width, the intermodal dispersion is 1.7 nsec.

4. DISCUSSION AND CONCLUSION

The Nanosecond Test Facility described above provides a simple, quick and effective means for measuring intermodal dispersion in multimode optical fibre waveguides. We have also discussed the various mechanisms that cause dispersion and the relative magnitude of each in various types of fibres. Measurement of dispersion in the fibre itself is important to determine the information carrying capacity of the fibre. We have used the Facility to carry out a systematic study[6] of dispersion in TELEBRÁS fibres. In particular, we investigated whether the Ray Propagation Model could be used to predict the dispersion and the length dependence of dispersion. The latter is of utrnost importance to investigate mode mixing effects and their influence on dispersion; these results are to be published shortly[16].

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