Revista Brasileira de Física, **Vol. 10, Nº 3, 1980**

Material Dispersion Measurements in Optical Fibre Waveguides

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Recebido em 17 de Dezembro de **1979**

We have carried out preliminary measurements of material dispersion on optical fibres now being routinely produced by TELEBRÁS in Brasil. This was done by using two semi conductor lasers emitting at the different wavelengths of 800 mm and 904 mm. Our result of -100 ps/nm/km in germania-doped silica fibres is -30% higher than the valeu for pure silica; this agrees well with results obtained in other laboratories with similar fibres. Material dispersion can limit the bandwidth of an optical fibre, especially when a light emitting diode, operating in the 800-900 mm wavelength region is used as the light source in a fibre optical communication system having graded-index fibres with an optimum index profile.

Concluimos medidas preliminares de dispersão material em fibras Óticas que vem, sendo produzidas rotineiramente pela TELEBRÁS no Brasil. Estas medidas foram feitas usando-se dois lasers semicondutores emitindo luz de diferentes comprimentos de onda, 800 mm e 904 nm. Nosso resultado de -100 ps/nm/km em fibras de silica dopadas com germânio *é* -30% maior que o valor para silica pure, o que está de acordo com resultados obtidos em outros laboratórios com fibras similares. Dispersão material pode limitar a largura de banda de uma fibra ótica, especialmente quando um diodo emissor de luz (LED), operando na região espectral entre 800 mm e 900 mm *é* usado como fonte de luz num sistema de comunicações por fibras Óticas tendo fibras de Índice graduado com um Ótimo perfil de Índice.

1. INTRODUCTION

In an effort to develop fibre optical communications systems within Brazil, we have already reported[1,2] results of the measurements of normalised mode conversion coefficients in fibres, which are now being routinely pulled at the "Padre Roberto Landell de Moura" Research and Development Centre of TELEBRÁS in Campinas. In our continuing programme to assess these fibres experimentally, we have used a Nanosecond Test Facility[3] to carry out a detailed and systematic study[4] of pulse dispersion in these fibres and the results will be reported shortly[5].

The total dispersion[6] in a multimode fibre is principally the sum of modal and material dispersion. Modal dispersion, sometimes also referred to as waveguide dispersion, is due to the different group velocities of the various modes propagating in the fibre. This was shown[7] very clearly using a ruby laser: with the excitation of all the modes, a very large dispersion was observed for the first time in a graded- index fibre. Material dispersion, also referred to as chromatic dispersion, is due to the wavelength dependence of the refractive index of the fibre core material and hence causes differences in the velocities among the frequency spectral components of the light source used. Both modal and material dispersion cause broadening of a narrow, sub-nanosecond, light pulse after propagation in the fibre, but the contribution of each can be markedly different depending on the light source used and the type of fibre excited with this source: (a) In a step-index multimode fibre, with all modes excited by a semiconductor laser, modal dispersion is large, about 30 ns/km for every per cent index difference between core and cladding. Since the spectral width of the laser is < 4 nm, material dispersion is negligible. This is also valid even with a light emitting diode, with an order of magnitude greater spectral width, (b) modal dispersion can be reduced drastically by using a gradeci-index fibre with an optimum index profile. If the light source is a semiconductor laser at 900nm, modal and material dispersion are comparable, being less than 1 nsec/km. However, if a light emitting diode is used, material dispersion can be upto three times greater than modal dispersion, as shown by Dawson[8].

Modal dispersion can be eliminated at any wavelength (λ) by designing a single-mode fibre for this wavelength with V, the normalised frequency parameter, having a value less than 2.405. It is given by

$$V = \frac{\pi d}{\lambda} (n_1^2 - n_2^2)^{1/2}$$

where d is the diameter of fibre core, n_1 is the index of fibre core and n_2 is the index of fibre cladding. Material dispersion can also be eliminated[q] when A is selected in the region of 1.3 µm, the exact wavelength for zero material dispersion depends on the core material, the dopant and its concentration[10].

Attenuation is also of great importance in the design of fibre optical systems as signals have to be regenerated. Recently it has been shown[11] that fibre attenuations of 0.2 dB/km, very near the theoretical Rayleigh scattering limit, can. be achieved at the wavelength of 1.55 µm. It is obvious that the ultimate fibre optical communication system consists of a single-mode fibre, designed to have zero material dispersion at this wavelength of minimum attenuation. Such a fibre has been demonstrated by Cohen et *al.*[12]. Since this type of system would transmit extremely high information capacities over very long distances, it would be fairly limited in its application, e.g., linking two large cities. There are many other applications where the systems could easily have much less bandwidths, but nevertheless in the tens of megabits per second range, by using fairly cheap and highly reliable light emitting diodes operating in the 800-900 nm wavelength region. With this in mind, we have made preliminary material dispersion measurements on optical fibres now being routinely produced in Brasil, so as to determine their information carrying capacities for diverse applications. Material dispersion measurements directly on the fibre itself are irnportant so as to know the total effect over the whole length of the fibre. Further, changescan occur due to severe thermal processing at about 2000°C during the fibre drawing process, thereby rendering any initial measurements on bulk samples invalid.

2. EXPERIMENTAL SET-UP

Our fibres, being multimode step-index types, have shown[4,5] a modal dispersion of ~20 nsec/km using 0.5 nsec pulses from a GaAs laser. Hence we could not use a light emitting diode to assess the material dispersion directly[8] as it would be difficult to separate the two effects. We have used an indirect method, first reported by Gloge *et al.*[13] and illustrated in figure 1. The principle of the method is very simple and is as follows: two pulses from lasers of different wavelengths are launched simultaneously into the fibre. The separation of the pulse peaks is measured before and after propagation and the difference gives the material dispersion. Laser L_1 was RCA SG 2001 emitting at 904 nm and Laser L_2 was type LD61, manufactured by Laser Diode Laboratories, emitting at 800 nm. Both were driven, from a common pulse generator, using separate identical circuits as described by Andrews[13]. The separation in the wavelengths $\Delta\lambda = 104$ nm, was much greater than 40 nm, the spread at the half-power points of a typical LED spectrum. This was chosen because our fibres were much shorter (-100 m) than that used Gloge *et al.*[13] (1000 m) and the modal dispersion was larger as well. Hence to observe a distinct

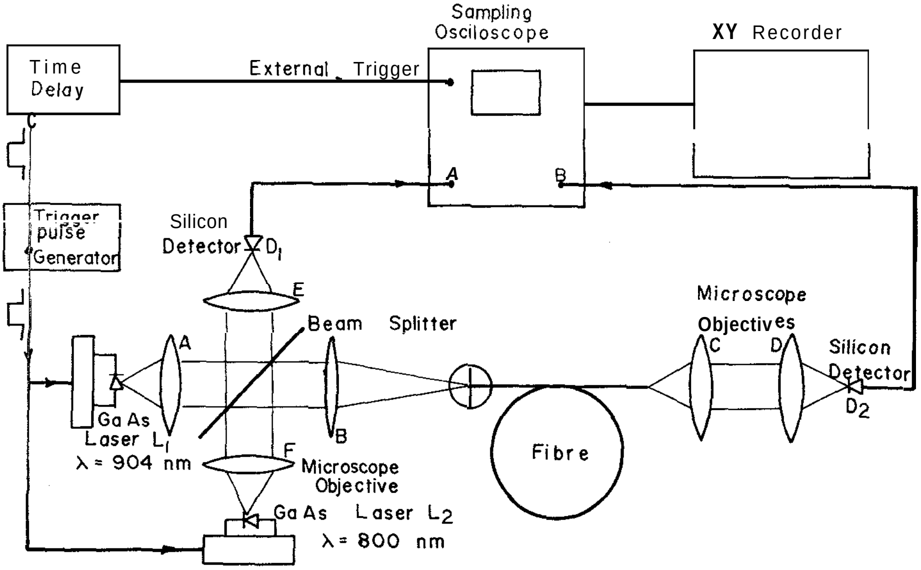

Fig.1 - Experimental set-up used to measure material dispersion in optical fibres.

difference in the separation of the two pulse peaks after propagation in the fibre, a larger $\Delta\lambda$ was required. However, knowing the normalised material dispersion in ps/nm/km, we can calculate the material dispersion expected using a light emitting diode having a peak wavelength of ~850nm and a spread of 40nm at the half-power points.

The lasers emitted light pulses of 0.5 nsec in duration. By using different lengths of cables from the pulse generator, the pulses were separated temporally so as to detect a difference in their separation after propagation. Microscope objectives A and F (x20, N.A. = 0.54) collimated the light spatially from these lasers and using a beam-splitter in the path of laser L_2, the pulses were launched into the fibre with the microscope objective B. We used a x5 objective so as to reduce the modal dispersion of the fibre by not exciting all the modes of the fibre. Detector D_1 detected the pulses being launched into the fibre, and hence their separation. Microscope objective C collimated the fibre output light and the objective D focused it onto detector D_2, which detected the pulses after propagation in the fibre. These detectorswere silicon avalanche photodetectors having a response of a few hundred picoseconds. The pulses were displayed on a Phillips Sampling Oscilloscope, Model PM 3400, and subsequently recorded on an X-Y plotter. Using the electrical delay, the oscilloscope was triggered first to observe the input pulses from detector D_1 and immediately afterwards the output pulses from detector D_2.

3. RESULTS

Fig. 2(a) shows the input pulse from Laser L_2 at 800 nm, with Laser L_1 blocked. The full width at half-maximum (FWHM) intensity points was 0.6 nsec. With all modes excited using a x10 microscope objective B, the output pulse, from 105 m of TELEBRÁS fibre 79, is shown in Figure 2 (b). This was a germania-doped silica fibre (GeO_2 - SiO_2). The FWHM was 1.8 nsec, giving a modal dispersion of 1.7 nsec after deconvolution of the input FWHM. This fibre showed a linear dependence[4,5] of modal dispersion, when we shortened the fibre progressively by 50 m steps from 350 m to 100 m, indicating fairly small mode conversion, i.e., very lit-

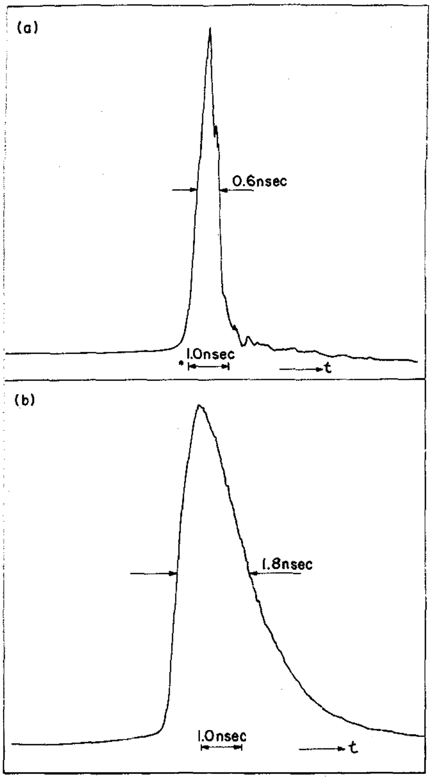

Fig.2 - (a) Input pulse to 105 m of fibre 79 from laser L_2 at 800 nm (FWHM = 0,6 ns); (b) Output pulse fron the fibre. (FWHM = 1.8 ns).

tle change in the angle of the light rays launched. Hence we extrapolated the modal dispersion in this fibre to be 17 nsec/km.

Fig. 3(a) shows the input pulses to the fibre from the two lasers, as detected by detector D_1. The pulse λ = 904 nm is to the right and the pulse λ = 800 nm is to the left. The pulse separation was 10.6 nsec. Fig. 3(b) shows the pulses after propagation in the fibre. The launching objective B was changed to x5 to reduce modal dispersion. The pulse separation reduced to 9.4 nsec due to material dispersion. The reduction takes place because the index of refraction at 904 nm is less than that at 800 nm and the former pulse travels at a faster velocity. Hence with AA = 104 nm, we observed a material dispersion of 1.2 nsec in 105 m of fibre 79. Normalising, as is usually done with material dispersion, we obtained 110 psec/nm/km. The numerical aperature (N.A.) of this fibre was measured to be 0.21. Another fibre, n? 74, also of GeO_2 - SiO_2 variety, (N.A. = 0.10), was also tested, giving a value of 96psec/nm/km.

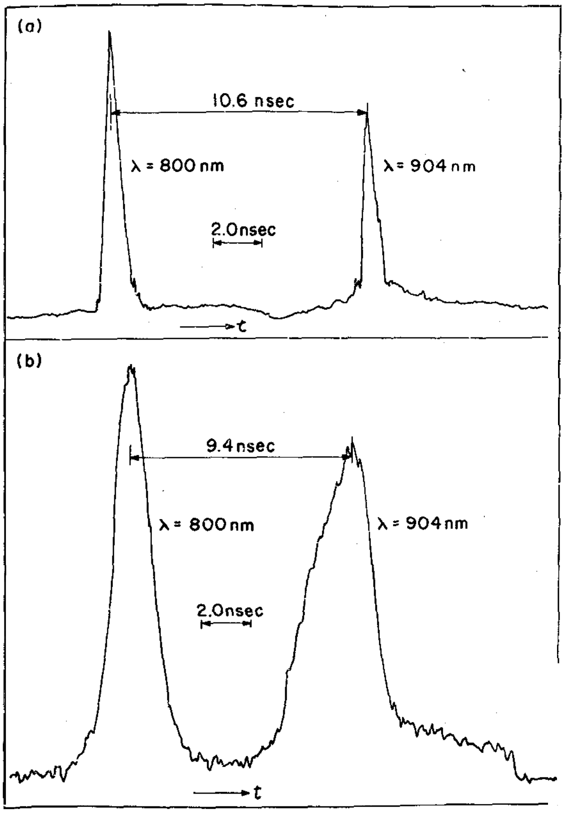

Fig.3 - The different wavelength pulses launched into the fibre, (a), and detected after propagation, (b), in 105 m of fibre 79. The λ = 904 nm pulse is on the right and the λ = 800 nm pulse is on the left. Pulse separation in (a) is 10.6 ns and in (b) is 9.4 ns.

4. DISCUSSION

The material dispersion ($\Delta\tau$), as determined from theory[13] is given by

$$\Delta\tau = \left(\frac{L}{c}\right) \cdot \left(\frac{\Delta\lambda}{\lambda}\right) \cdot \left(\lambda^2 \cdot \frac{d^2n}{d\lambda^2}\right) \text{ seconds} ,$$

where L is length of fibre, λ is the peak wavelength, Δλ is the spectral spread of the light source used and n is the refractive index of core.

The second derivative of the index with respect to the wavelength ($\frac{d^2n}{d\lambda^2}$) determines the material dispersion. We can compare our results with calculations made for pure silica. We do so by taking, for fibre 79, $L=105m$, $C = 3 \times 10^8$ m/s, $\Delta\lambda = 104$ nm, $h = 850$ nm, and $(\lambda^2 \frac{d^2n}{d\lambda^2}) = 0.022$ from figure 3 of Gloge's paper[15]. Hence we obtain $\Delta\tau = 0{,}94$ nsec compared to a value of 1.2 nsec observed experimentally, being approximately 30% higher. Comparing this with the results obtained in other laboratories (references 10, 13, 16, 17) we note that a similar effect of increased material dispersion was also measured in $GeO_2 - SiO_2$ fibres at 850 nm. We have summarized these results in Table I. We have not considered measurements on bulk samples[18,19], for reasons already outlined, and also results[20] outside the wavelength of 850 nm, which is of main interest in this paper. Material dispersion of pure silica at 850 nm is 85 psec/nm/km. Since the germania concentrations are not known in all the fibres in Table 1, we have indirectly assessed this by evaluating the numerical aperature of each fibre from the data provided; an increased GeO_2 concen-

Reference	Peak A (nm)	Material dispersion measured. (ps/nm/km)	Fibre numerical aperture
Gloge[13]	880	90	0.09
Presby and Kaminow[16]	850	115	0.29
Miyashita *et al.*[17]	850	91	0.13
Payne and Hartog[10]	900	95	?
Sunak and Ayres Neto (this work)	850	96	0.10
Sunak and Ayres Neto (this work)	850	110	0.21

Table I - Material dispersion measurements in germania-doped silica fibres.

tration would give the fibre core a higher refractive index n_1 and hence increase its numerical aperature, given by $(n_1^2 - n_2^2)^{1/2}$, where n_2 is the refractive index of the pure silica cladding.

We have plotted material dispersion as a function of numerical aperature in figure 4. A fairly good linear relationship is observed. From the formula given above, we note that only the second derivative of the core index with respect to the wavelength $\left(\frac{d^2n}{d\lambda^2}\right)$ changes the material dispersion, with L, $\Delta\lambda$ and λ held constant. The results of figure 4 could be justified only if the slope of the refractive index curve, with wavelength, varied progressively more rapidly with increasing concentration of GeO_2, and hence increasing numerical aperature. This was indeed shown very clearly, by the measurements made by Kobayashi et *al.*[18], on bulk samples of pure silica doped with different amounts of germanium. This would also seem to imply that measurements carried out on the fibre itself are in qualitative agreement with measurements made on small bulk samples. Work is to be carried out to investigate this further and to obtain quantitative results of the dependence of material dispersion on GeO_2 concentration measured in the fibre itself. From the results of Presby and Kaminow[16], it can be seen that, of the six dopants used, germanium has the most pronounced effect in increasing the material dispersion. In B_2O_3 - SiO_2 fibres, the material dispersion decreases very

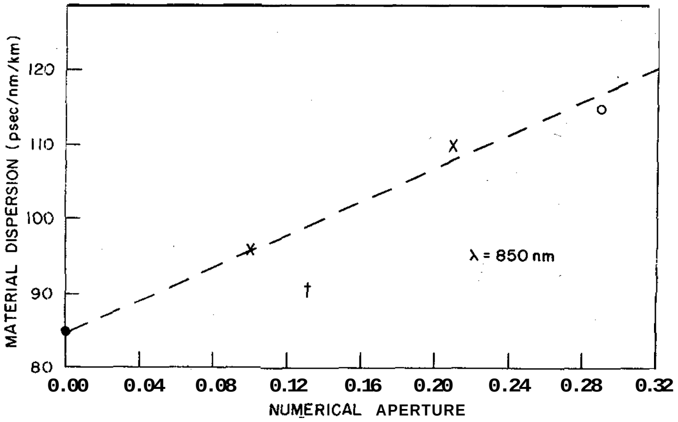

Fig.4 - Material dispersion, at 850 nm, in GeO_2 - SiO_2 fibres as a function of numerical aperature (O - after Presby and Kaminow[16]; + - after Hiyashita et *al.*[17]; x - this work, ● - material dispersion of pure silica).

slightly whereas in P_2O_5 - SiO_2 fibres, no change as compared to pure silica, is observed. As stated earlier, only in single-mode or optimum graded-index multimode fibres, the effect of each dopant on the fibre bandwidth would have to be considered carefully for systems design at a particular wavelength. However, in step-index multimode fibres, the effect of increased material dispersion, even with high GeO_2 concentrations, is negligible as discussed below.

Our fibre 79 had a modal dispersion (τ_g) of 17 nsec/km. Assuming that we used a light emitting diode of 40 nm spectral width at 850 nm, we would have an additional material dispersion (τ_m) of 4.4 nsec/km. Assuming Gaussian pulse shapes, the total broadening (τ) in 1 km of fibre would be $\tau^2 = 17^2 + 4.4^2$, giving τ = 17.6 nsec. Hence it is clear that the bandwidth of our fibre is limited by modal dispersion. This was to be expected as fibre 79 is of the multimode step-index type. We can calculate, conservatively, the maximum pulse bit rate (B) possible in our fibres using $B = (2\tau)^{-1}$ for unity mark/space ratio. Hence B = 28.4 Mbits /sec over a l km length. If τ_g is reduced to 4 nsec/km by designing a graded-index multimode fibre, using the same light source, we would obtain τ = 6 nsec and B = 84 Mbits/sec. Hence fairly large bandwidths are still possible using highly reliable light emitting diodes operating at 850 nm, and systems using these sources will have many diverse applications.

5. CONCLUSION

We have used two GaAs lasers of different wavelengths and measured a material dispersion of 110 psec/nm/km in GeO_2 - SiO_2 fibres at a wavelength of 850 nm. This result is in good agreement with previous results, showing an increase of ~30% from the value of 85 psec/nm/km for pure silica. We also conclude that modal dispersion dominates material dispersion in multimode step-index fibres but transmission rates of many tens of megabits per second over one kilometer can still be achieved.

We would like to thank Telecomunicações Brasileiras S/A (Telebrás) for financially supporting this work and supplying the fibres. One of us, (J.B.M. Ayres Neto) also thanks FAPESP for a post-graduate scholarship, and is now with Centro de Pesquisas e Desenvolvimento, Telebrás, Campinas, São Paulo.

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