University of Geneva **Faculty of Sciences**

Section of Physics
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DISPERSION EFFECTS AND MEASUREMENT IN OPTICAL WAVEGUIDES

Summary in English of the

Ph. D. Thesis

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by

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I Introduction

Single-mode guided optics have recently taken a predominant place in communications systems. For instance single-mode fibers enable long span, high data rate transmission links to be installed. In such fibers the data rate is ultimately limited by the *chromatic dispersion*, that is, the spectral variations of the propagation time.

It will first be shown that chromatic dispersion is the fundamental limit to the data rate. Then, the dispersive properties of optical fibers will be described.

The chromatic dispersion is experimentally deduced by differentiating the propagation delay measurements with respect to the wavelength. The experimental challenge is to measure the propagation delay with a 1 ps resolution per kilometer of fiber continuously over the full 1200 to 1600 nm spectral range. It has never been achieved so far. For this purpose two complementary experimental methods are proposed.

On one hand, an interferometric method has been developed enabling meter-length fiber samples to be measured. Fiber birefringence can also be estimated by this technique without using any polarizing devices. On the other hand, a novel phase shift method using a double optical modulation has been achieved enabling long installed fibers to be measured.

II Light propagation through a dispersive medium

Assuming a propagation through a single transverse mode, a polychromatic light source can be considered as an incoherent superposition of single longitudinal mode - or monochromatic - sources, each having a different angular frequency ω_i, an arbitrary phase ϕ_i and its own field amplitude E_i.

When this source is modulated, each longitudinal mode is split into a coherent superposition of modes, that is, each frequency of the source is divided into a set of sidebands. These sidebands are characterized by their frequency Ω_k relative to the carrier, and by a complex coefficient b_k representing the amplitude and phase relationships with respect to the carrier.

The light intensity after propagation throughout a length L of the dispersive medium reads:

$$<I(t,L)> \;=\; \frac{1}{2}\,\varepsilon_o\,c\,\sum_i E_{oi}^2\,\left|\,\sum_k b_k\,e^{-i\,\beta(\omega_i+\Omega_k)\,L}\;e^{-\frac{1}{2}\,\alpha(\omega_i+\Omega_k)\,L}\;e^{i\,\Omega_k\,t}\,\right|^2 \qquad (1)$$

where $\beta(\omega)$ is the propagation constant or effective wavenumber and $\alpha(\omega)$ is the linear attenuation coefficient.

The propagation constant is usually expanded in a Taylor's serie around the central frequency ω_o of the source:

$$\beta(\omega) \;=\; \beta_o \;+\; \beta'\cdot(\omega-\omega_o) \;+\; \frac{\beta''}{2}\cdot(\omega-\omega_o)^2 \qquad (2)$$

where β' represents the group delay per unit length and β'' is directly related to the dispersion by the relation:

$$D \;=\; -\frac{2\pi c}{\lambda^2}\,\beta'' \qquad (3)$$

where D is the propagation time difference per unit wavelength and per unit length.

The expression (1) can be calculated in two important situations: the sinusoidal modulation and the Gaussian pulse.

Sinusoidal Modulation

Assuming the temporal dependence of the light intensity at the input to be:

$$<I(t,0)> \;=\; I_o\,\frac{1}{2}\,(\,1 \;+\; \cos\Omega t\,) \qquad (4)$$

where Ω is the modulation angular frequency, the intensity at the output can be calculated using (1):

$$<I(t,L)> \;=\; I_{oL}\,\frac{1}{2}\left\{\,1 \;+\; |g_L(\Omega\beta''L)|\,\cos\left[\,\Omega\,(t-\beta'L) \;+\; \phi_g(\Omega\beta''L)\,\right]\right\} \qquad (5)$$

where I_{oL} is the mean output intensity, $|g_L|$ is the *first order degree of coherence* of the light and ϕ_g is an unimportant phase factor.

The signal is therefore delayed of the quantity $\beta'L$ - the propagation time related to the group velocity - and its amplitude is reduced by the factor $|g_L(\tau)|$ which is always smaller than 1 for $\tau\neq0$. The typical width of $|g_L|$ is directly related to that of the spectral distribution $\Delta\omega$, allowing an expression to be established for the bandwidth of the transmission link:

$$\Omega \le \frac{1}{2\,\Delta\omega\,|\beta''|\,L} \tag{5}$$

Gaussian Pulse

Let us assume the temporal behavior of the intensity of a pulse to be Gaussian with a 1/e−width τ. Let us consider the spectral distribution of the source to be also Gaussian with a 1/e−width $\Delta\omega$.

The expression (1) yields the following expression for the width of the pulse as a function of the propagation length L:

$$\tau(L) = \sqrt{\tau^2 + (\beta'' L)^2\,(1/\tau^2 + \Delta\omega^2)} \tag{7}$$

Considering a polychromatic source ($\Delta\omega >> 1/\tau$), the pulse broadening becomes a limitation when

$$\tau \le |\beta''|\,L\,\Delta\omega \tag{8}$$

which is for a pulse a condition equivalent to (6).

The effect of dispersion is independent of the kind of light involved (chaotic, coherent or non−classical), mainly because the dispersion is only a phase effect, that is, it does not change the photon statistics. In fact, considering a single mode of the source, the photon destruction operator at the output end is equivalent to the source destruction operator **a** multiplied by a dispersion−dependent phase factor when applied to the n−photon state |n>.

III Effects of dispersion in optical fibers

Let n_1 the refractive index of the central region or *core*, n_2 the index of the outer region or *cladding* and a the core radius. The propagation constant β of the fiber can be written:

$$\beta = k\sqrt{n_2^2 + b\,(n_1^2 - n_2^2)} \quad , \quad 0 < b < 1 \tag{9}$$

where k is the vacuum wavenumber and b is the normalized propagation constant which is the eigenvalue of the wave equation for a particular index profile shape (step index, triangular, multiple cladding, etc.) and is

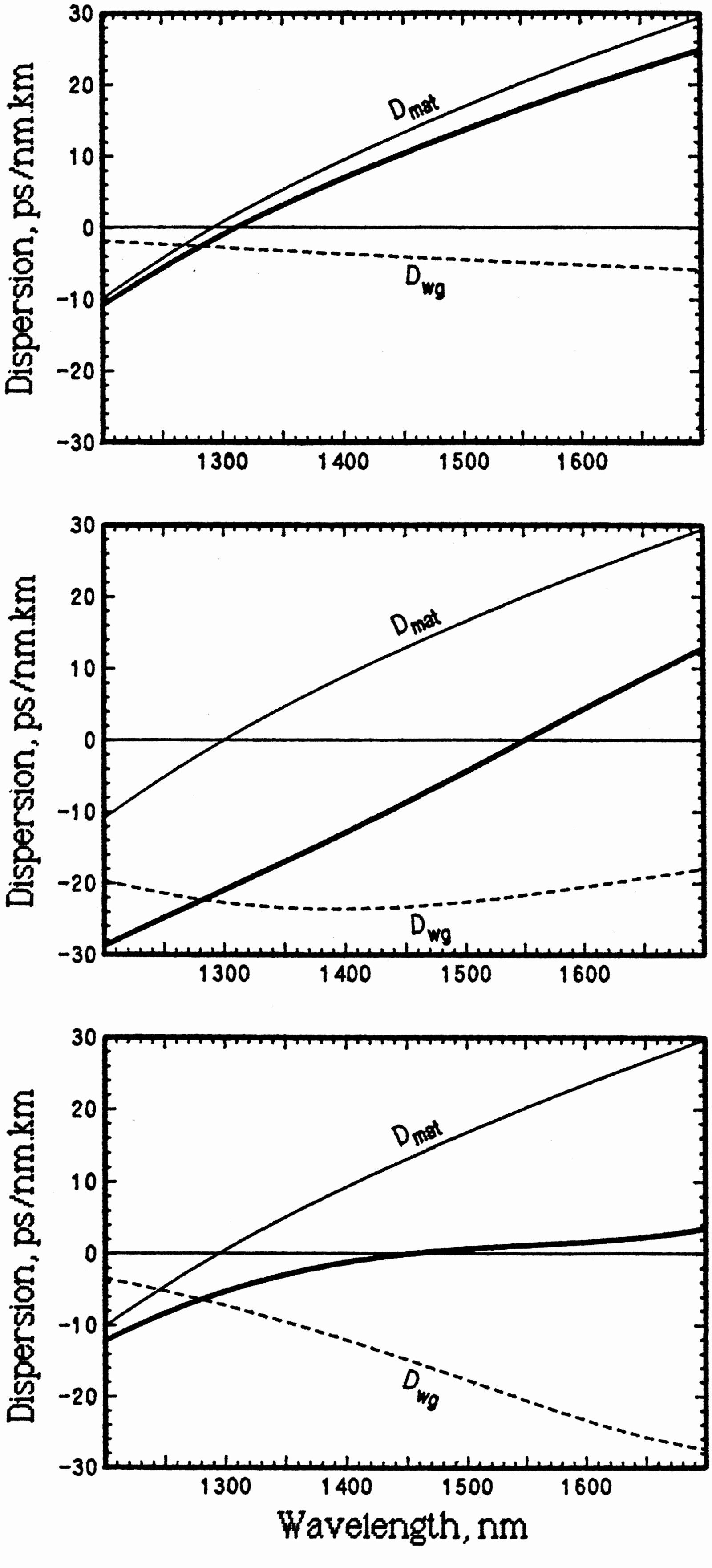


Fig. 1 Material, wave-guide and total dispersion of fibers having different refractive index profiles, so that the dispersion curve is either standard, shifted or flattened respectively.

only a function of the normalized frequency $V = k\,a\,\sqrt{n_1^2 - n_2^2}$.

The chromatic dispersion D is deduced from the expression (9):

$$D = \frac{d^2\beta}{d\lambda\, d\omega} = D_{mat} + D_{wg} \tag{10}$$

The first contribution, the material dispersion D_{mat}, depends critically on the dispersive properties of the materials constituting the dielectric waveguide. This term can be explicitly expressed as:

$$D_{mat} = \frac{1}{\lambda c}\left\{ D_2 + (D_1 - D_2)\,\frac{d(bV)}{dV} \right\} \tag{11}$$

where $D_i = -\lambda^2 \dfrac{d^2 n_i}{d\lambda^2}$.

In silica optical fibers the material dispersion is zero near 1300 nm, in the spectral region of minimum intrinsic attenuation.

The second contribution, the waveguide dispersion D_{wg}, is a consequence of the guiding and even exists when the waveguide materials are non-dispersive. It reads:

$$D_{wg} = -\frac{1}{\lambda c}\,(N_1 - N_2)\,\frac{N_2}{n_1}\,V\,\frac{d^2(bV)}{dV^2} \tag{12}$$

where $N_i = n_i - \lambda \dfrac{dn_i}{d\lambda}$.

The magnitude of this term strongly depends on the shape of the refractive index profile.

Actually the material dispersion is dominant, but the dispersion curve can be noticeably modified by properly choosing the profile shape, so that the curve is shifted to longer wavelengths or even flattened on a wide spectral range, as shown in Fig. 1.

IV Interferometric measurement of dispersion

When polychromatic light is launched into an interferometer, interferences are only observed if the difference between the group delays in each arm is smaller than the coherence time of the light. When one of the arms - the test arm - is dispersive and the length of the other arm - the reference arm - is scanned, interferences are found at different positions for different wavelengths owing to the spectral variations of the group

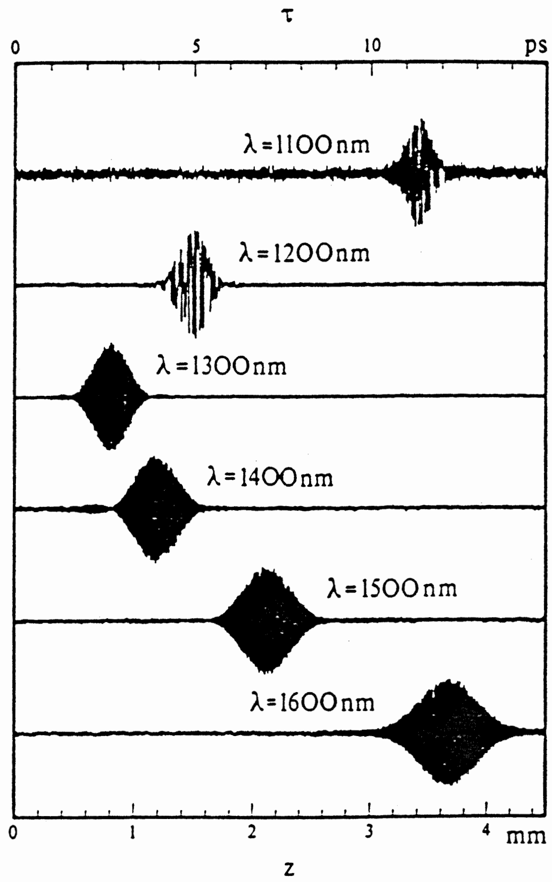


Fig. 2 Interferences measured by scanning the length of the reference arm for different wavelengths, showing the spectral variations of the propagation delay.

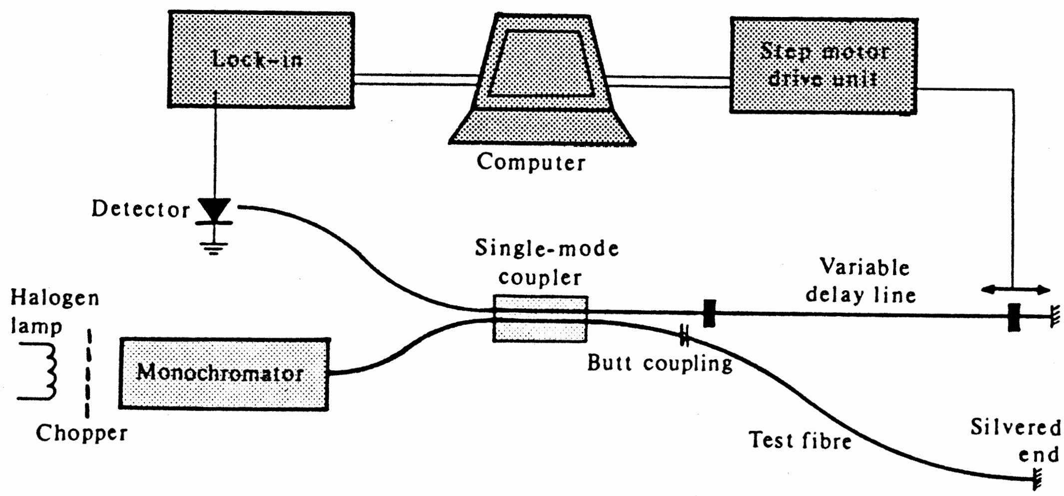


Fig. 3 Schematic diagram of the experimental setup.

velocity. This feature is shown in Fig. 2 using an optical fiber.

Use of a classical interferometer for systematic measurements would be tedious, because the two beams must perfectly overlap for a proper reconstruction, making the alignments uneasy. For this reason a novel all-fiber interferometer has been developed for which the schematic diagram is shown in Fig. 3. The main features of the setup are:

- A Michelson configuration minimizing the optical elements and doubling the dispersion effect, the light propagating twice through the fiber sample;
- A single-mode fiber coupler for the interferometric reconstruction, so that the overlap is perfect without the need of any alignments;
- A fiber reference arm for which the length can be varied using its elastic properties, so that the light remains confined in the waveguide.

The light source was a halogen lamp for which the continuous spectrum was scanned by a monochromator, and the detector was an InGaAs photodiode. The whole experiment was fully controlled by a desk-top computer (wavelength selection, reference arm length, light intensity measurement).

The length of the all-fiber reference arm was varied by simply elongating the fiber. But the optical path change is not equivalent to the elongation since the refractive index changes when a stress is applied. The conversion factor was measured and was found to be 1.17 ± 0.0008. This factor can be considered as wavelength-independent over the 1200-1600 nm spectral range with a good confidence level.

Fig. 4 shows a dispersion measurement as a function of wavelength achieved by using the above described setup. The length of the fiber sample was 1.85 m. The group delays can be measured using this setup over the full 1000-1730 nm spectral range with a measured standard deviation of 0.5 ps/km.

Measurement of Polarization Mode Dispersion

Birefringence can be induced in single-mode fibers either accidentally during the manufacturing process or intentionally to obtain polarization preserving fibers. Classical techniques use properly oriented polarizing devices or retardation plates for the measurement of birefringence, which is

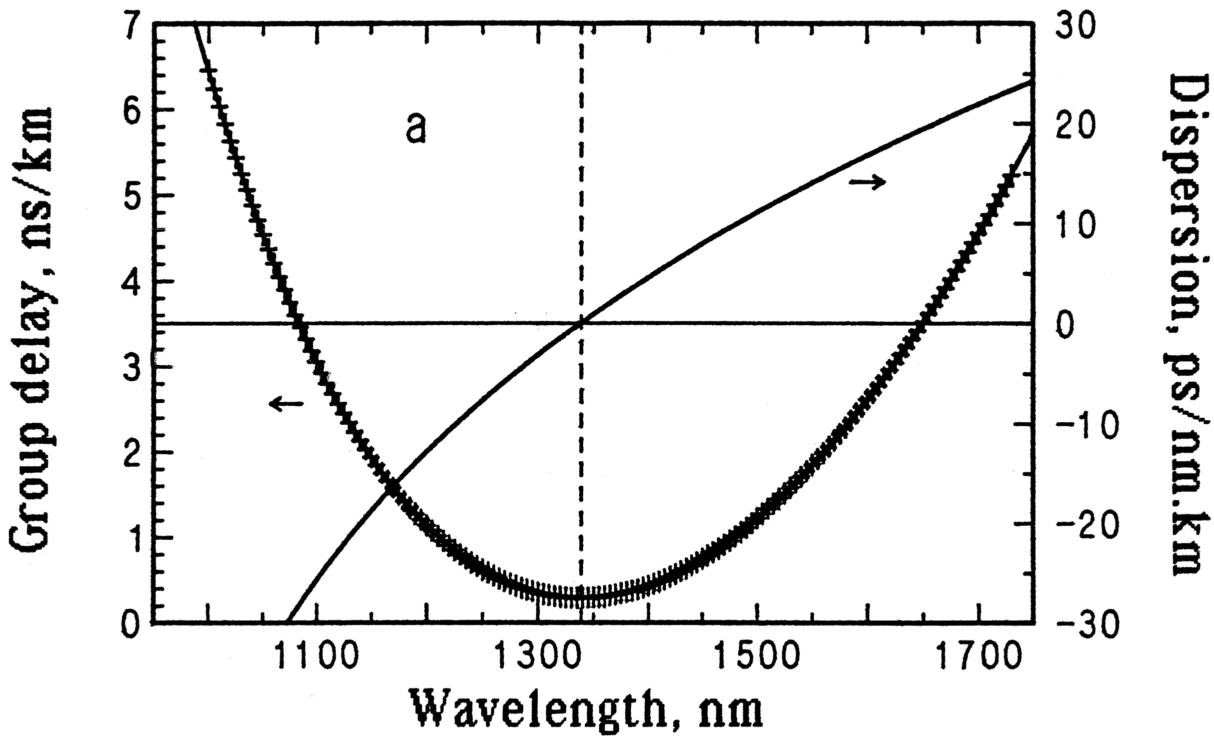


Fig. 4 *Interferometric group delay measurement of a step index fiber as a function of wavelength and resulting dispersion curve.*

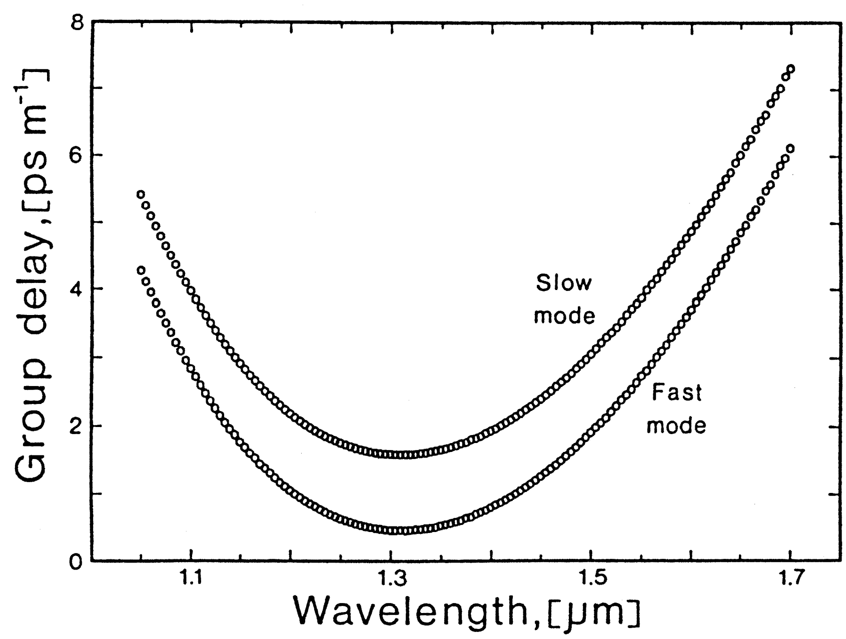


Fig. 5 *Separate group delay measurement of each polarisation eigenmode of a highly birefringent fiber as a function of wavelength.*

directly related to the delay between polarization modes. The interferometric method enables the measurement of polarization mode dispersion (*PMD*) to be made in a simple way using the same above described setup. In particular, it requires no polarizing devices and no special alignments or fiber preparation. In addition it can be simultaneously performed with a chromatic dispersion measurement.

Since interferences cannot occur between light in orthogonal polarization states, each polarization mode gives rise to an independent interferometric reconstruction. When the fiber sample is highly birefringent, the delay between polarizations is so large that the interference patterns of each polarization mode are well separated. This way the group delay of each polarization eigenmode can be independently measured as a function of wavelength, as shown in Fig. 5. The difference between these two group delay curves yields the polarization dispersion.

This technique can, however, only be used when the separation between the interference patterns is greater than the light coherence length. For example with this setup, the 9.5 nm spectral width resulted in a minimum measurable polarization dispersion of 0.4 ps/m.

When the birefringence is accidentally induced in standard fibers, it is much smaller and the interference patterns completely overlap. Therefore the direct method described so far can no longer be used. Nevertheless the birefringence can be evaluated using the same setup, but with another technique.

When the wavelength of the source is scanned, the overall interference contrast periodically varies because the birefringence makes the relative phase between the interferometric reconstructions of each polarization mode depends on wavelength, as shown in Fig. 6a. The period of this spectral variation of contrast is directly related to birefringence and can be simply found by performing a Fourier transform, shown in Fig. 6b. The resolution on polarization dispersion is improved to 0.003 ps/m using this technique.

V Dispersion measurement using a double optical modulation

Many techniques have been developed to measure dispersion on long installed fibers and, among them, phase shift methods have taken a predominant place. In this class of method a wide spectrum source - or a set

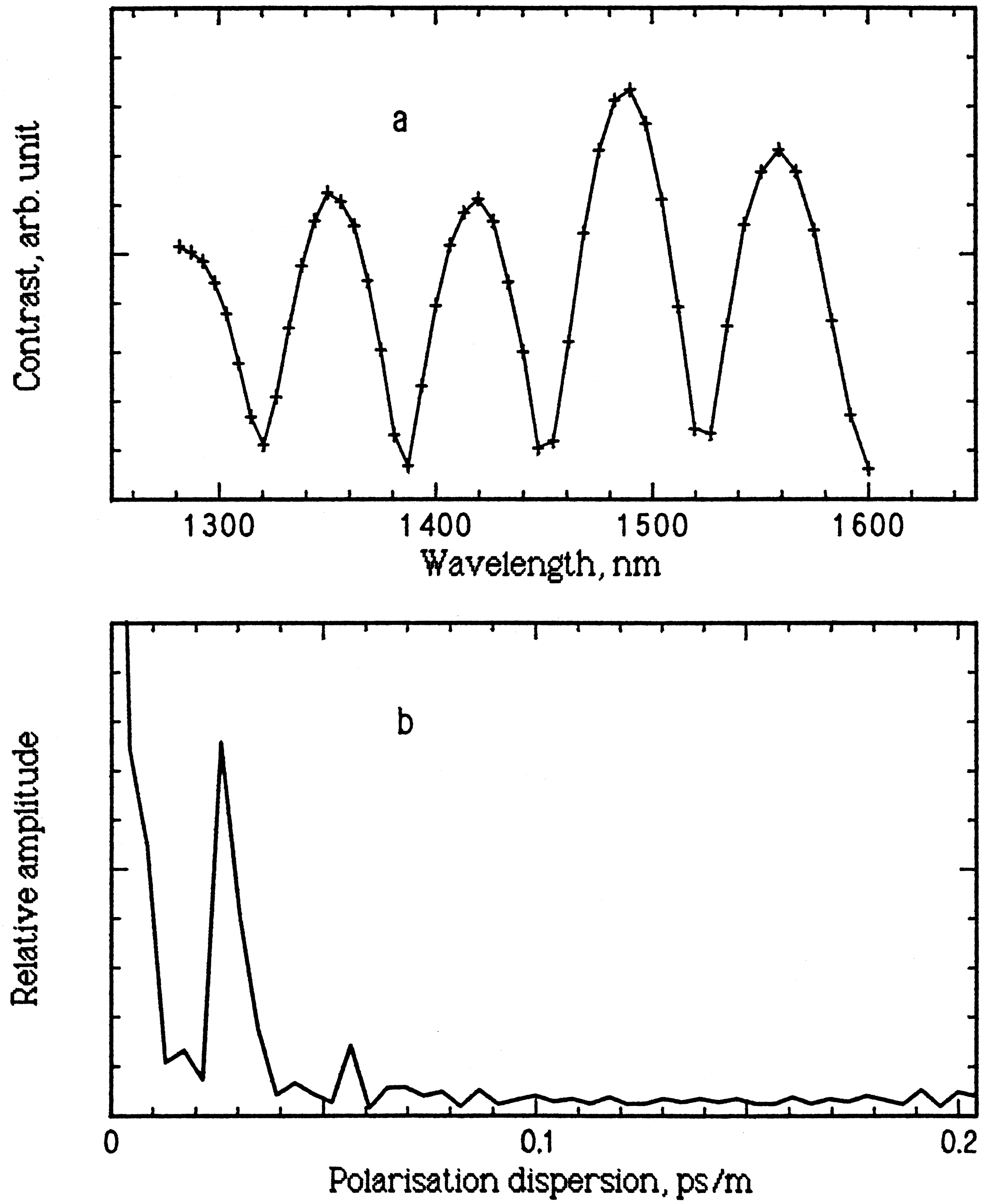


Fig. 6 *a: Overall interference contrast as a function of wavelength, measured using a 1.85 m weakly birefringent fiber as test arm. b: Corresponding Fourier transform; the peak position gives the polarisation dispersion value.*

of monochromatic sources - is sinusoidally modulated to a high frequency. The group delay variations give rise to phase shifts with respect to a reference signal when the source spectrum is scanned.

In order to obtain a sufficient resolution, the modulation frequency must be in the 100 MHz range. Therefore wideband detector and preamplifier with a consequently high noise level are required. Since the spectral density of wide spectrum sources is low, the detected intensity is very small after a spectral filtering by a monochromator. Hence a poor dynamic range results and the measurement is strongly perturbed and biased by radio–frequency interferences radiated by the cables.

A novel phase shift method was therefore developed which eliminates these drawbacks. This was actually achieved by downshifting the modulation frequency to the low–frequency range right before detection, using a second optical modulation. The basic diagram of the method is shown in Fig. 7. This re–modulation splits the signal into sum– and difference–frequency components, each keeping the phase of the incident signal. Thus the time resolution is unchanged by this signal processing. By properly choosing the re–modulation frequency, the difference–frequency may lie in the kilohertz range, enabling an ultra–sensitive low–frequency detection scheme and an ultra–stable phasemeter to be used. This results in a considerably improved reliability and in a dynamic range which is several orders of magnitude better.

The main difficulty to build this experiment was to find a suitable light source and modulation devices operating at such a high frequency.

The Light Source

Three types of light sources were actually tested: light emitting diodes, halogen lamps and fluorescent neodymium–doped fibers.

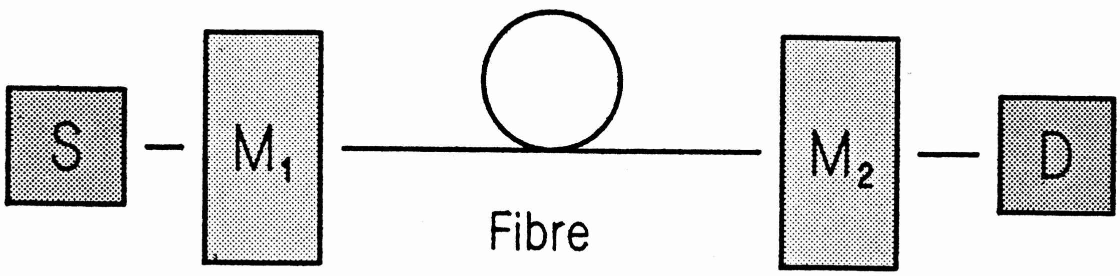


Fig. 7 Basic diagram of the double optical modulation method. S: source; $M_{1,2}$: intensity modulators; D: detector.

Light emitting diodes (LED) have a high spectral density at their nominal emission wavelength, but have a moderatly wide spectrum with a half-maximum width of about 80 nm. Actually two optically coupled LED are at least required for a full coverage of the 1200 to 1600 nm spectral range. However, the main advantage of LED is their capability to be directly modulated at a high frequency through their drive current, allowing the first modulation device to be no longer required. Best results were obtained using this type of source.

The black body spectrum of the halogen lamp is almost uniform over the spectral range of interest and is thus ideal for dispersion measurement. But the source must be modulated by an external modulator and its low spectral density makes it of little practical use. Nevertheless measurements were successfully performed in a 4 km fiber using such a lamp.

The neodymium-doped fiber emits a wide fluorescence spectrum while pumped by an AlGaAs semiconductor laser at 800 nm. The spectral density obtained near 1300 nm remains much lower than with a LED and this source is therefore of no advantage.

The Modulator

Two types of intensity modulators operating in the proper frequency range were actually tested: the acousto-optic modulator and the integrated electro-optic modulator.

In order to obtain a higher modulation frequency, the acousto-optic modulator was used in a special way by strongly focussing the light on the acoustic wave. Hence the direct and diffracted beams overlap in the focussing cone and, since their optical frequency is different, a beat signal is generated at the acoustic wave frequency. This method for modulation requires careful alignments.

Better results were obtained using a Mach-Zehnder integrated optics modulator on a $LiNbO_3$ substrate. Such a device enables a higher modulation frequency and an all-fiber optical configuration to be achieved, together with a better stability and reliability.

Results

Fig. 8 shows a schematic diagram of the experimental setup. The source is two optically coupled LED, directly modulated through their drive current.

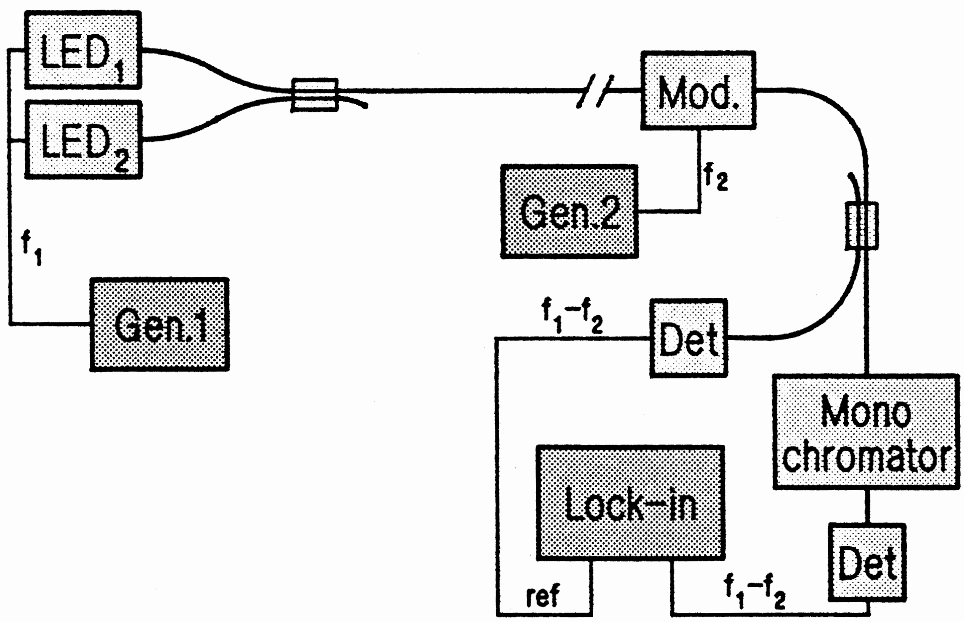


Fig. 8 Schematic diagram of the experimental setup using an optical reference.

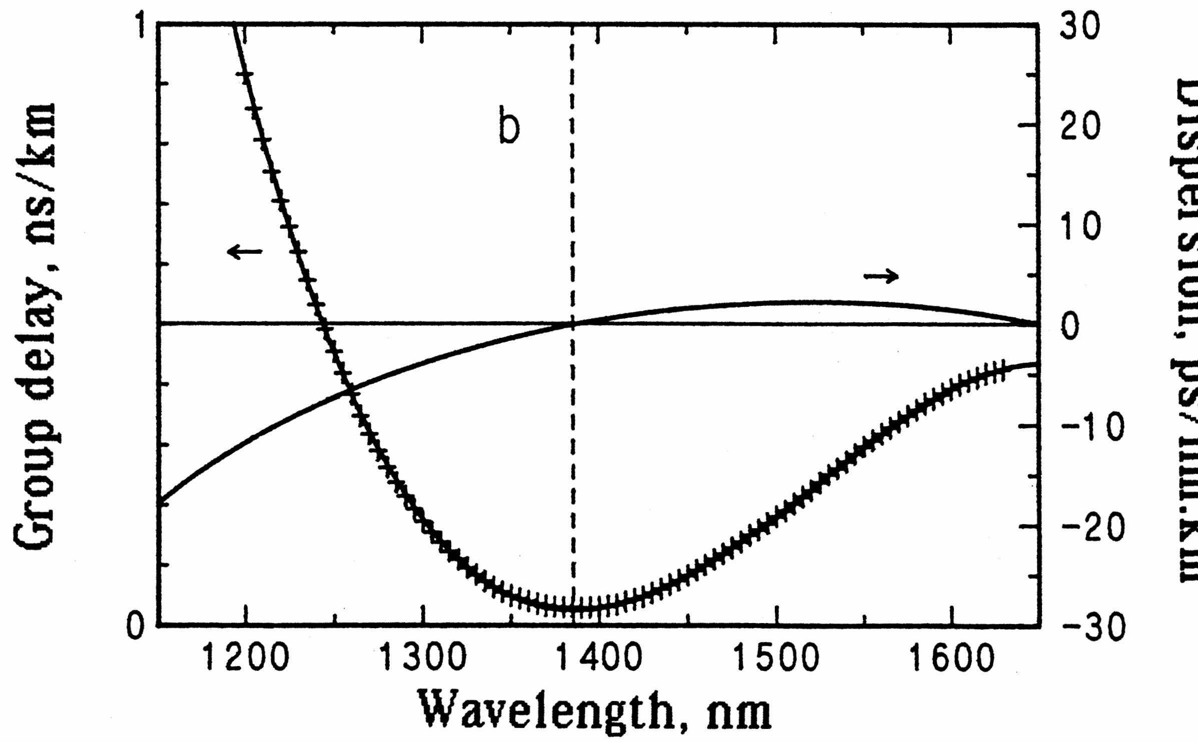


Fig. 9 Group delay measurement as a function of wavelength of a 3.8 km dispersion-flattened fiber and resulting dispersion curve.

The second modulation is performed using an integrated optics modulator. The reference signal is optically generated by detecting part of the light intensity before the monochromator, so that a spectrally averaged signal is available, which remains constant during the whole measurement process. This enables the measurement to be performed even when the fiber ends are remote without requiring another link for the reference signal.

Fig. 9 shows a measurement of a 3.8 km dispersion-flattened fiber achieved using this setup. The full 1200-1600 nm spectral range is covered. The 300 MHz modulation frequency and the 0.1° phase resolution results in a 0.93 ps time accuracy, so that a 1 ps/km group delay accuracy can be obtained using less than 1 km of fiber. The standard deviation on zero-dispersion wavelength is less than 0.1 nm. The dynamic range at the peak emission wavelength of the LED is 33 dB.

VI Conclusion

It was widely known that chromatic dispersion measurement requires delicate optical circuits and ultra-fast instrumentation. Both the above described methods deny this statement, because they are basically designed to be easy to operate and to use ordinary reliable low-frequency instrumentation.

This was achieved by systematically replacing classical elements by guided-wave devices (fiber, coupler, EO modulator) and by optically processing the signal as much as possible. We thusceed to achieve a 1 ps/km group delay resolution over the full 1200 to 1600 nm spectral range on either a sample or a long installed fiber. Highest accuracy could therefore be obtained for the chromatic dispersion calculation.

VII Publications and conferences

Further informations concerning this work can be found in the following publications and conference proceedings:

1) L. Thévenaz, J.P. Pellaux, J.P. von der Weid, " All-fiber Interferometer for Chromatic Dispersion Measurements ", IEEE J. Lightwave Technol., **LT-6**, pp. 1-7, (1988)

2) J.P. von der Weid, L. Thévenaz, J.P. Pellaux, " Interferometric Measurements of Chromatic and Polarization Mode Dispersion in Highly Birefringent Single-Mode Fibres ", Electron. Letters, **23**, pp. 151-152, (1987)

3) L. Thévenaz, V. de Coulon, J.P. von der Weid, " Polarization-Mode Interferometry in Birefringent Single-Mode Fibers ", Optics Letters, **12**, pp. 619-621, (1987)

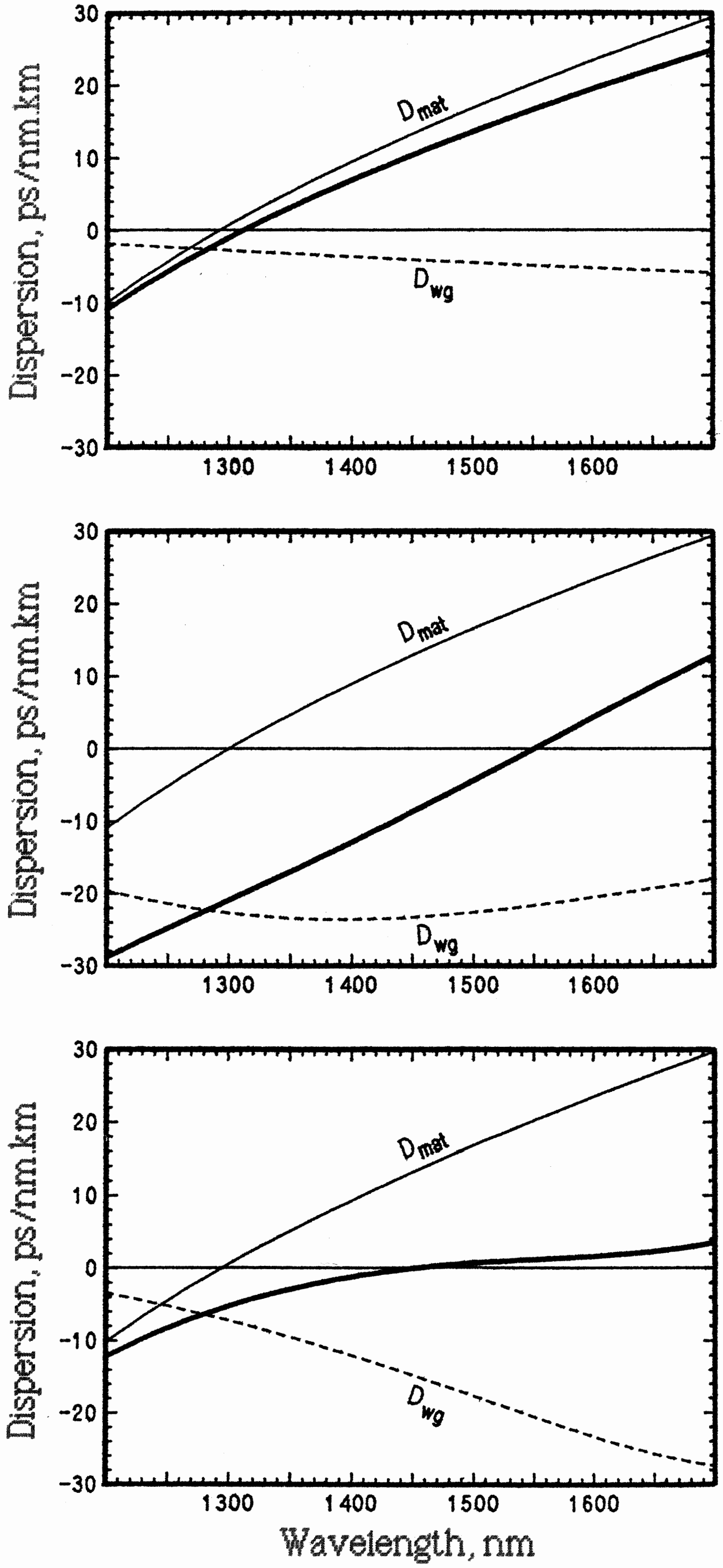
4) L. Thévenaz, J.P. Pellaux, " Modulation Frequency-Shift Technique for Dispersion Measurements in Optical Fibres using LEDs ", Electron. Letters, **23**, pp. 1078-1079, (1987)

5) L. Thévenaz, J.P. Pellaux, " Group Delay Measurement in Single-Mode Fibers with True Picosecond Resolution using Double Optical Modulation ", IEEE J. Lightwave Technol., (1988), accepted for publication.

6) L. Thévenaz, J.P. Pellaux, J.P. von der Weid, " Birefringence Characterization of Fibres without Polarizer ", *in* Proceedings of 13th European Conference on Optical Communications, Helsinki, Vol. I, pp. 205-208, (1987)

7) L. Thévenaz, J.P. Pellaux, " Shifted Modulation Frequency Technique for Chromatic Dispersion Measurements ", *in* Technical Digest of 1987 Annual Meeting of the Optical Society of America, Rochester, contribution WY6, pp. 98, (1987)

8) L. Thévenaz, J.P. Pellaux, " Modulation Frequency-Shift Technique for Dispersion Measurements in Optical Fibers ", *in* OFC'88 Technical Digest, Optical Fiber Communications conference, New Orleans, contribution WM2, (1988).



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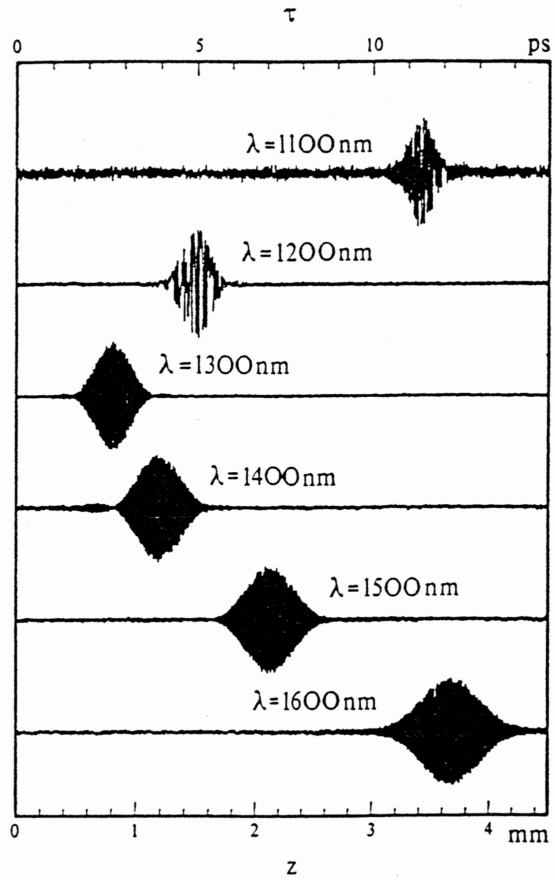

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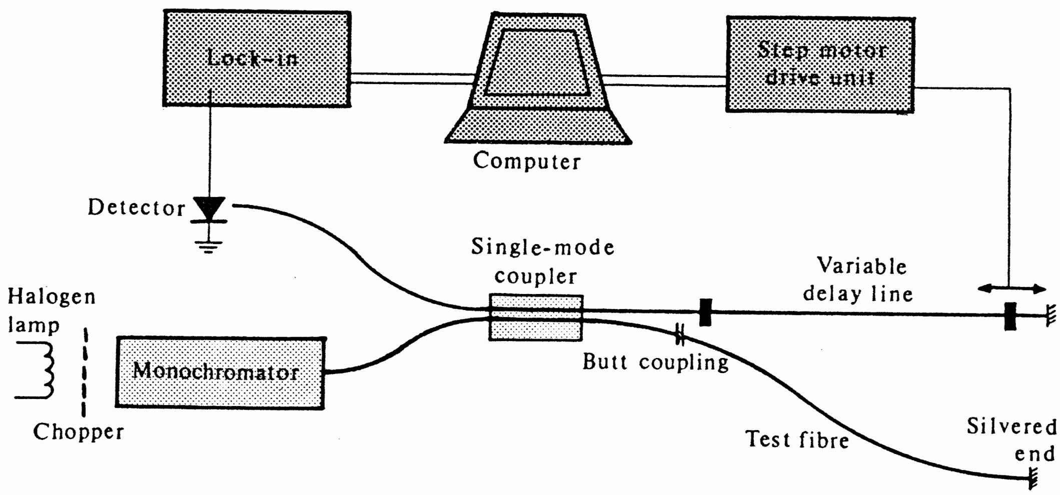

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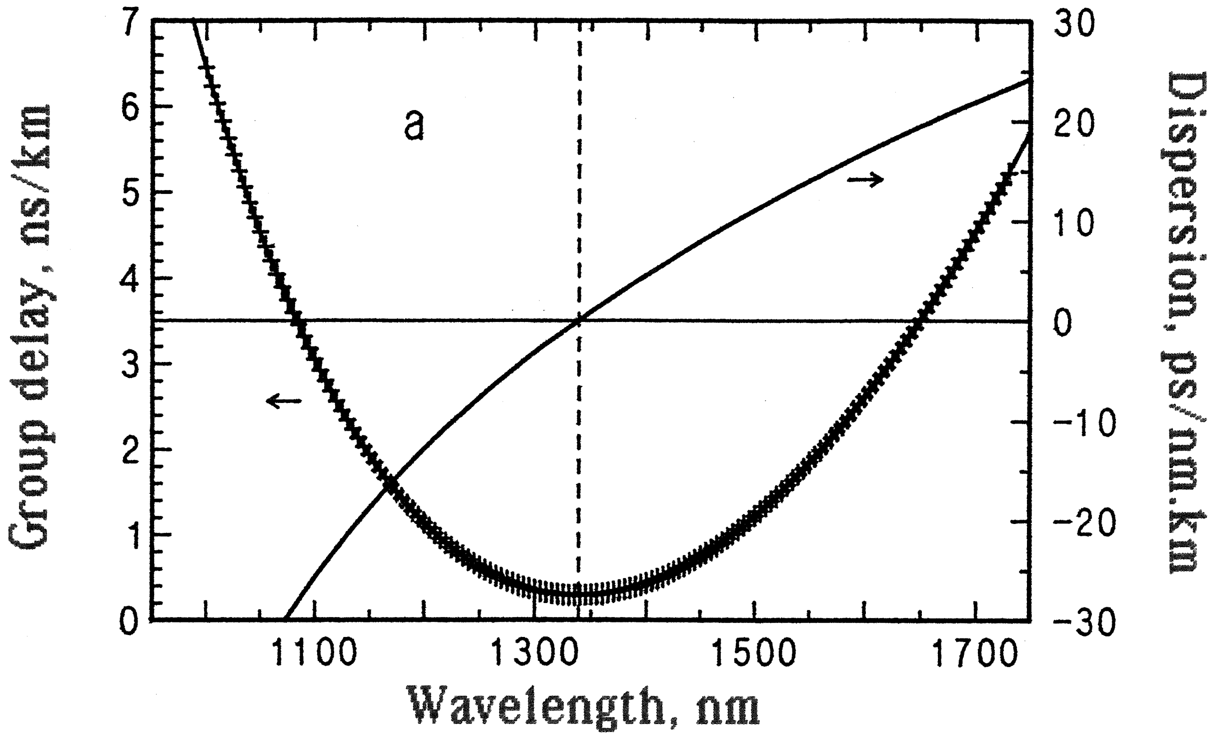

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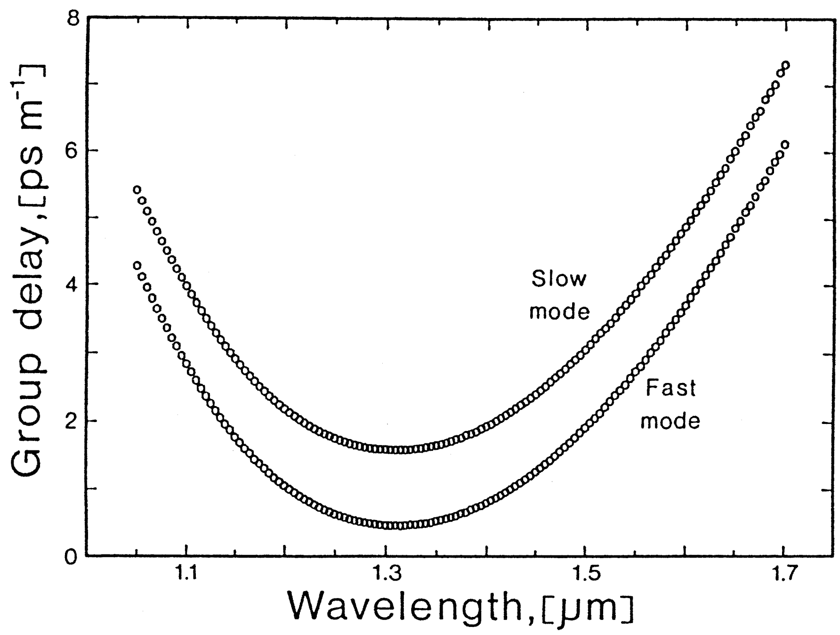

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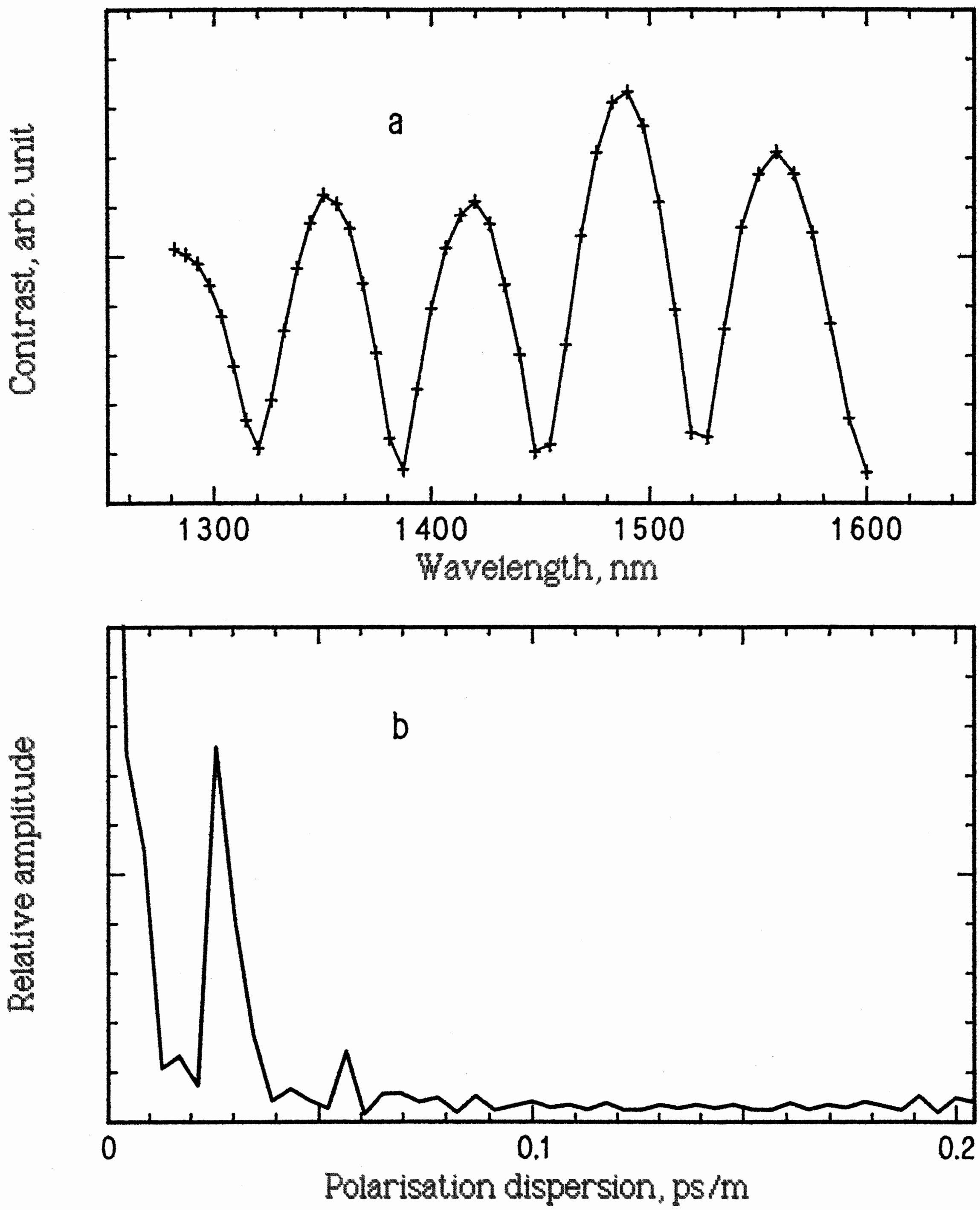

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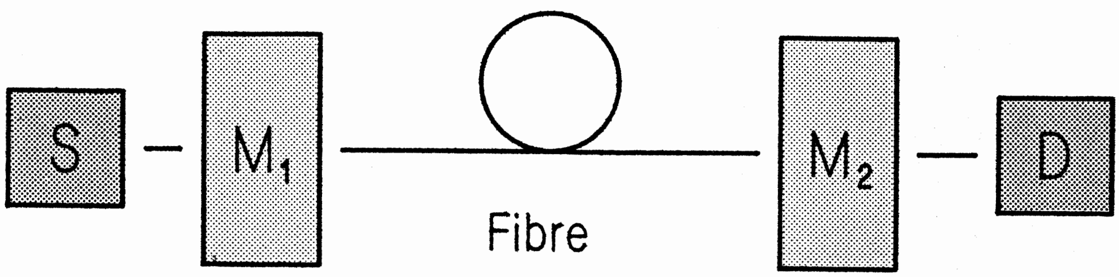

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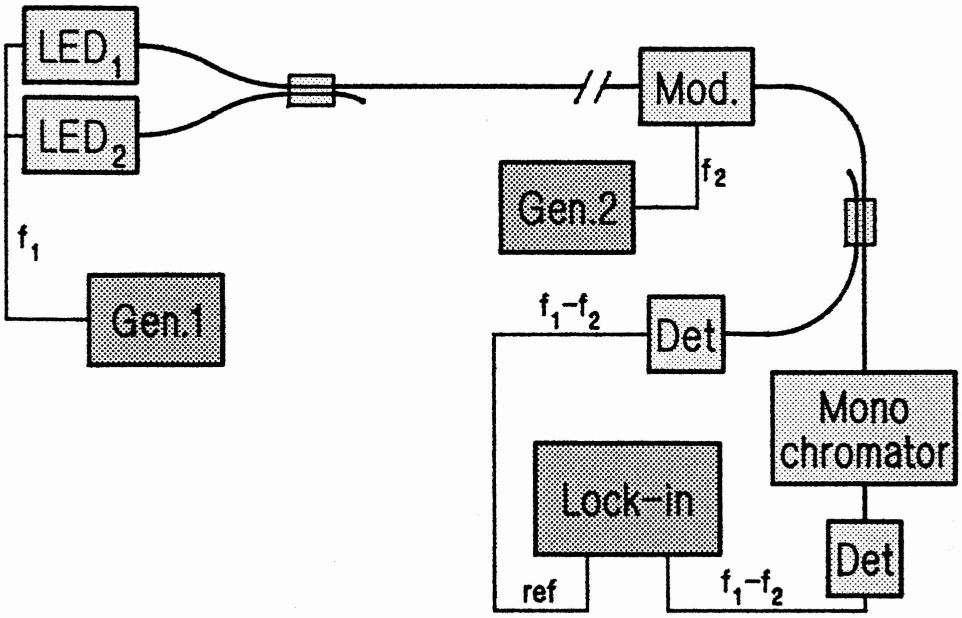

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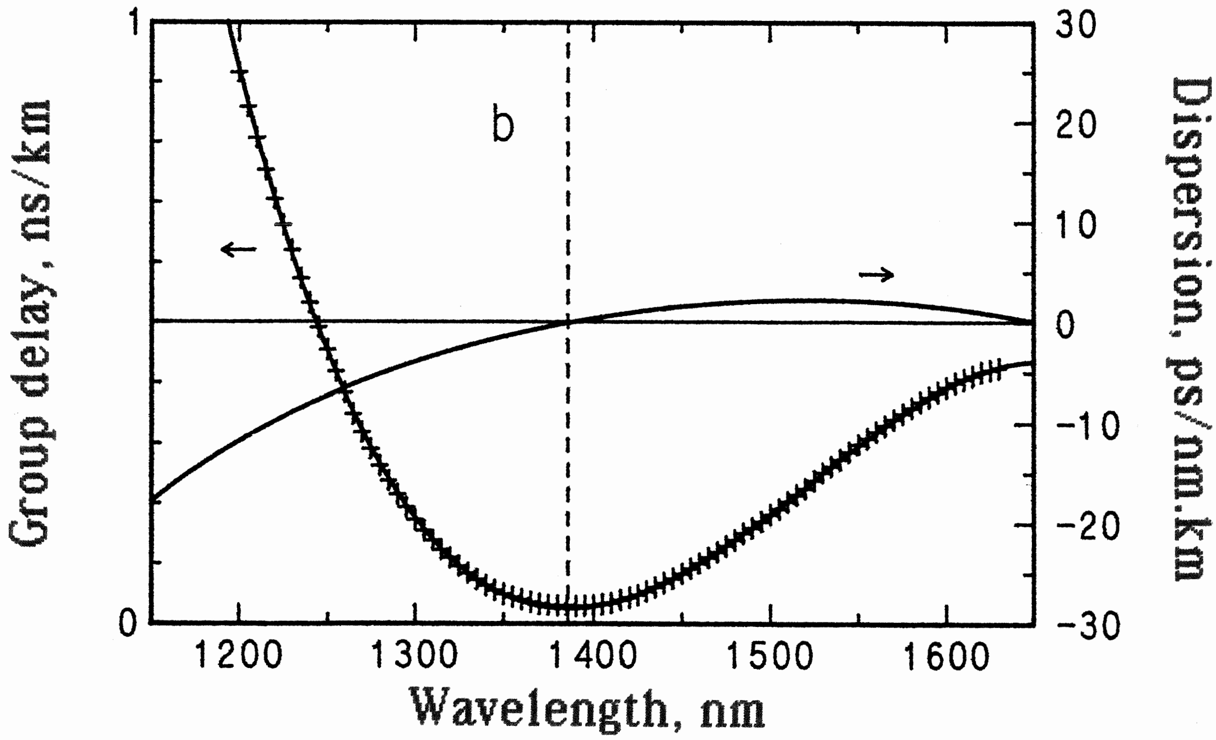

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