Group Delay Measurement in Single-Mode Fibers with True Picosecond Resolution Using Double Optical Modulation

LUC THÉVENAZ AND JEAN-PAUL PELLAUX

Abstract—**Highly accurate group delay measurements in long single-mode fibers were achieved over the full 1200–1600 nm spectral range by measuring phase shifts of a modulated lightwave. The high modulation frequency is shifted down to the kilohertz range using a second optical modulation at the fiber output end, so that low-frequency ultrasensitive detection and phase measurement can be performed with high-frequency resolution conserved. This results in extremely reliable measurements with a < 1-ps resolution using a fully remote light source such as a LED or even a halogen lamp.**

I. Introduction

THE MEASURE of chromatic dispersion of single-mode fibers is of greatest importance to insure optimal performance in the data rate capability of an optical link. For this purpose an ideal setup should allow group delay measurements with picosecond resolution in a broad wavelength range. Although these conditions seem difficult to meet, many experimental methods have been proposed to date such as fiber Raman lasers [1] and interferometric techniques [2]. Unfortunately they suffer from inherent drawbacks: the former method requires an expensive setup and involves safety hazards. The latter technique provides high resolution measurements in the all-fiber configuration [3] together with accurate information on birefringence properties without requiring polarizing devices [4], [5], but remains restricted to short samples.

These drawbacks have given a predominant place to phase shift techniques. In this class of methods a wide spectrum source is sinusoidally modulated and the group delay is deduced from the modulation phase shift of fiber output light when the spectrum is scanned. For this purpose LED's are suitable light sources owing to their relatively wide spectrum and high frequency modulation capability [6]. The spectral scan is performed by filtering the LED spectrum with a monochromator. The main problem arising with this technique is the low intensity of the filtered light resulting in a poor signal-to-noise ratio and strong phase fluctuations. Furthermore, radio-frequency interference due to the strong LED drive current perturbates the measured signal providing biased measurements. These problems can be reduced only by using extreme care and advanced techniques [7].

In this paper we report a technique giving improved phase shift measurements using optical signal processing. This novel method combines the advantages of good resolution due to high-frequency modulation and the extreme sensitivity and reliability due to low-frequency detection and signal processing. The method fully eliminates the main problems encountered with phase shift techniques, even improving the performance.

II. Basic Principles

A schematic diagram of the experiment is shown in Fig. 1. It is basically the same configuration as a classical phase shift method, except a second intensity modulation performed at another angular frequency Ω_2 just before detection. This additional optical processing generates sum- and difference-frequency components of the modulated signal enabling low-frequency detection and measurement to be made, since Ω_2 can be chosen arbitrarily close to Ω_1.

This can be demonstrated in a more rigorous way by developing the optical field over its longitudinal modes $|\omega_i\rangle$. They are characterized by their optical angular frequency ω_i, a single transversal mode being assumed. The usual harmonic behavior is given by the following scalar product:

$$\langle t|\omega_i\rangle = e^{i\omega_i t} \tag{1}$$

In this experimental configuration the electric field on the detector is represented by the following ordered operators:

$$\boldsymbol{E}(L) = \boldsymbol{M}_2\boldsymbol{D}(L)\,\boldsymbol{M}_1\boldsymbol{E}(0) \tag{2}$$

where

$$\boldsymbol{E}(0) = \sum_i E_{0i}\,|\omega_i\rangle\,\langle\omega_i|$$

is the field emitted by the source, developed over its modes. The light source is assumed to be chaotic and spectrally filtered. Also:

$$\boldsymbol{M}_1 = \sum_j a_j\,|\omega + j\Omega_1\rangle\,\langle\omega|$$

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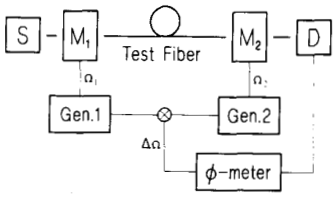

Fig. 1. Schematic diagram of the experiment. S: source, M_1: source modulation, M_2: second optical modulation, D: detector.

is the source modulation, which can be internal or external to the light emitting device. The summation includes the different overtones that can possibly be generated. Their relative amplitude and phase are represented by the complex coefficients a_j. In addition

$$\boldsymbol{D}(L) = e^{-i\beta(\omega)L} e^{-(1/2)\alpha(\omega)L} |\omega\rangle \langle\omega|$$

represents the propagation through the dispersive medium, where $\beta(\omega)$ is the propagation constant and $\alpha(\omega)$ the optical attenuation, and

$$\boldsymbol{M}_2 = \sum_k b_k |\omega + k\Omega_2\rangle \langle\omega|$$

is the second intensity modulation at the fiber output end.

The detected intensity then corresponds to this average value:

$$\langle I(t, L)\rangle = \tfrac{1}{2}\epsilon_0 c \overline{\langle t | \boldsymbol{E}^+(L)\, \boldsymbol{E}(L) | t\rangle} \tag{3}$$

where the bar denotes that an ensemble average has to be performed. In order to evaluate this expression, the propagation constant $\beta(\omega)$ is expanded in a Taylor's serie around the median frequency ω_0:

$$\beta(\omega) = \beta_0 + \beta'(\omega - \omega_0) + \frac{\beta''}{2}(\omega - \omega_0)^2 \tag{4}$$

where the primes denote differentiations with respect to ω. Since $\Omega_1 << \omega$ and the light modulation bandwidth is limited, the following approximation also holds for a given mode:

$$\alpha(\omega_i + j\Omega_1) \simeq \alpha(\omega_i), \qquad \text{for all } j \tag{5}$$

which in fact means that the optical sidebands created by the modulation undergo an attenuation equivalent to the fundamental.

Using (4) and (5), expression (3) for the intensity contains many frequency components and most of them are in fact not used, being eliminated by filtering in the phasemeter. For this reason the calculation of the frequency component $\Delta\Omega = \Omega_1 - \Omega_2$ is sufficient, yielding:

$$\begin{aligned}\langle I_{\Delta\Omega}(t, L)\rangle &= \tfrac{1}{2}\epsilon_0 c \sum_i |E_{0i}|^2 e^{-\alpha(\omega_i)L} e^{-i\beta''(\omega_i-\omega_0)\Omega_1 L} \\ &\quad \cdot \sum_{j,k} a_j a_{j-1}^* b_{k-1} b_k^* e^{i[\Delta\Omega t - \Omega_1\beta' L + (\beta''/2)(1+2j)\Omega_1^2 L]} \\ &\quad + \text{complex conjugate.}\end{aligned} \tag{6}$$

In this last expression the terms depending on different indices are separated and the summations can therefore be independently performed. Taking into account the continuous nature of the source spectrum, the summation over the modes represented by the index i, is converted into an integral by introducing the following normalized spectral distribution:

$$E_{0i} = E_0 F(\omega_i - \omega_0)\, d(\omega_i - \omega_0),$$

$$\text{with} \int |F(\omega_i - \omega_0)|^2 d(\omega_i - \omega_0) = 1 \tag{7}$$

giving, after substitution:

$$\begin{aligned}\sum_i |E_{0i}|^2 e^{-\alpha(\omega_i)L} e^{-i\beta''(\omega_i-\omega_0)\Omega_1 L} &= |E_0|^2 \int |F(\omega_i - \omega_0)|^2 e^{-\alpha(\omega_i)L} \\ &\quad \cdot e^{-i\beta''(\omega_i-\omega_0)\Omega_1 L} d(\omega_i - \omega_0) \\ &= |E_0|^2 g_L(\beta''\Omega_1 L)\end{aligned} \tag{8}$$

where g_L is the Fourier transform of the power spectrum *on the detector* and is therefore the *degree of first-order temporal coherence* of the light at this location.

Before performing the summation over the indices j and k, another approximation can be made by neglecting the phase term $(\beta''/2)(1 + 2j)\Omega_1^2 L$. This term is in fact a second-order correction on the sideband phase velocity with respect to the fundamental and it can be shown to be actually much smaller than the measured phase shifts. The remaining terms to be summed no longer depend on the propagation parameters of the fiber and can be condensed by letting:

$$\sum_{j,k} a_j a_{j-1}^* b_{k-1} b_k^* = A_1 e^{i\phi_1} \tag{9}$$

where A_1 and ϕ_1 represent the relative real amplitude and the phase of the signal frequency component $\Delta\Omega$ respectively, without considering the propagation effects. Substituting (8) and (9) into (6), the detected intensity at the frequency $\Delta\Omega$ takes the much simpler form:

$$\langle I_{\Delta\Omega}(t, L)\rangle = I_0 \operatorname{Re}\left\{A_1 g_L(\beta''\Omega_1 L)\, e^{i[\Delta\Omega t + \Omega_1\beta' L + \phi_1]}\right\} \tag{10}$$

where

$$I_0 = \tfrac{1}{2}\epsilon_0 c |\mathcal{E}_0|^2.$$

The group delay β' and the signal phase depend on each other according to a linear relationship, the modulation frequency Ω_1 and the fiber length L being scaling parameters. It can be shown that the function g_L is real only if the power spectrum is symmetrical, that is, when the median frequency ω_0 and the mean frequency $\bar{\omega}$ are equal. When the spectrum is assymmetrical, g_L is complex and an additional phase term ϕ_g depending on β'' appears in (10), acting as a biasing parameter in phase measure-

ments. This phase term means that the median frequency ω_0 is no longer representative of the source spectrum, as far as dispersive effects are concerned. This restriction is not relevant to the present experiment, but holds for general phase shift methods using light with a broad spectral spread.

On the other hand, the modulus of g_L has its maximal value at the origin, g_L being an autocorrelation function. Its effect is thus to decrease the signal amplitude when the dispersion increases.

The detected intensity is thus given by the following expression:

$$\langle I_{\Delta\Omega}(t, L)\rangle = I_0 A_1 \left| g_L\left(D \frac{\lambda^2}{c} f_1 L\right)\right| \cdot \cos\left[\Delta\Omega t + \Omega_1 \beta' L + \phi_1 + \phi_g\right] \tag{11}$$

showing that phase shift measurements due to high-frequency modulation can be performed at another arbitrary frequency—which can be in the low-frequency range—using a second optical modulation.

III. Experimental Setup

In order to achieve group delay measurements over a wide spectral range, the optical and optoelectronic devices involved in this experiment must operate and be efficient over a broad spectrum. Considering light sources, only polychromatic emitting devices are suitable for convenient spectral coverage, requiring on the other hand a monochromator for spectrum scanning and filtering. Light emitting diodes (LED's) are particularly interesting because they have a moderately wide spectrum ($\Delta\lambda \simeq 80$ nm) together with high-frequency modulation capability. This last possibility makes them very attractive, the same device combining the functions of source and modulator. Furthermore, their high spectral density near their peak emission wavelength results in a high dynamic range, enabling measurements over long optical fiber links. The spectral coverage can be increased by using two LED's with different peak wavelengths and by optically coupling their light outputs.

Another possible light source is the halogen lamp, which shows a nearly uniform emission over the whole spectral range of interest, however at a very low level. Besides, such a source requires an external device for performing the necessary high-frequency modulation. The unavoidable intrinsic loss of such devices consequently reduces the light intensity even more. Nevertheless, group delay measurements on several kilometers of fiber were performed thanks to the ultrasensitive detection stage used in this experiment.

The main experimental difficulty of this method is the achievement of the high-frequency light modulation over a wide spectral range at the fiber output end. Previously this modulation was successfully performed using an acoustooptic modulator [8], but it required careful optical alignments and the overall modulation efficiency was strongly wavelength dependent. The recent commercial availability of integrated optic devices provides a new solution to the problem of high-frequency light modulation. We tested optical guided-wave Mach–Zehnder interferometers using Ti : $LiNbO_3$ technology, performing intensity modulation up to the gigahertz range. These modulators are specially designed to operate at one nominal wavelength, typically 1300 or 1550 nm. Since chromatic dispersion measurement requires a wavelength scan, the spectral behavior of such devices has to be characterized. For this purpose we measured the peak-to-peak amplitude of the light modulated by the device at different wavelengths, yielding the actual loss after normalization. Two devices were tested, named hereafter A and B, especially designed to operate at 1300 and 1550 nm, respectively.

Results for unpolarized incident light are shown in Fig. 2. Because the waveguides are designed to carry the lowest order TE mode, the output light is polarized, so that a 3-dB loss is to be expected. Another 1.5-dB contribution results from the intrinsic attenuation of the crystal, the remaining loss being due to the waveguide imperfections together with the coupling to the fiber pigtails. The operating spectral range is bounded by the effective cutoff of the single guided mode for the longer wavelengths and by the cutoff of the higher order mode for shorter wavelengths. Thus device A can actually be used from 1100 to 1500 nm and device B from 1200 to 1700 nm. The former is therefore suitable only for measurements in the 1300-nm transmission window, while the latter can be used in both low-loss transmission windows and is therefore preferred for this application.

In addition to their inherent reliability and high bandwidth, these devices offer the possibility of building an experimental setup using only guided-wave optics, that is, requiring neither lenses nor air paths. This results in a much better mechanical and optical stability, eliminating most disalignment hazards. Moreover the coupling efficiency between optical elements is fully achromatic.

Light detection is performed by a pig-tailed InGaAs p-i-n photodiode used in the low-noise photovoltaic mode owing to the low-frequency measurement signal. The remaining noise level can be further reduced using a lock-in amplifier for the phase measurement. The lock-in integration time is adjusted depending on the photoelectric signal, so that a constant signal-to-noise ratio is maintained for any signal amplitude, resulting in constant phase measurement fluctuations. Therefore the weaker the signal, the larger the required integration time constant, giving rise to a longer measurement duration. The signal is considered to be no longer measurable when the integration time must exceed 3 s, giving so a lower bound for the dynamic range determination. The inherent stability and strong filtering capability of the lock-in amplifier provide results with better reliability, emphasizing another advantage of a low-frequency measurement signal.

A phase measurement always requires a reference signal of the same frequency. This signal must be indepen-

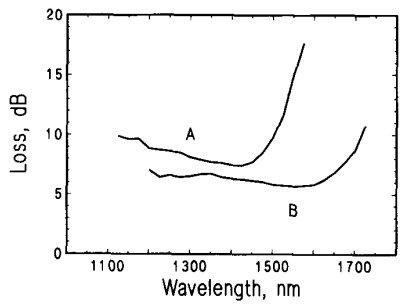

Fig. 2. Modulation loss of two optical guided-wave intensity modulators as a function of wavelength for unpolarized incident light. Nominal operating wavelength: $A = 1300$ nm, $B = 1550$ nm.

dent of experimental input variables. That is, for group delay measurement, it must not depend on wavelength. In this experiment it can be electrically generated by mixing and filtering the signals supplied by the generators driving the source and second optical modulations. But this solution is difficult to achieve when the source and the second modulation together with the detector are remote. The distance between them can be several kilometers for an installed optical link.

In this case another solution is to use the optical signal propagating through the fiber under test as the reference signal. It is rendered wavelength independent by performing the wavelength selection by means of the monochromator *after* the second optical modulation, just before detection. This has of course no effects on the measured signal, but the optical signal at the monochromator input has the proper frequency $\Delta\Omega$ and contains the whole measurement spectrum, resulting in a spectrally averaged signal. Thus a small part of this signal can be derived and used as a reference signal after detection and shaping.

The diagram of an experimental setup achieved using such an optical reference is shown in Fig. 3. At the input end of the fiber under test, there is only a stable generator and the source, in this case two LED's merged by a single-mode coupler. At the receiving end the second optical modulation is immediately performed, driven by another stable frequency generator. A single-mode coupler then derives a small part of the light, which is detected and electronically shaped in order to be used as reference signal. It should be noticed there is no electrical link between the high- and low-frequency parts of the setup, resulting in very good immunity to undesired interferences. Furthermore all signal processing is achieved in the low-frequency range for best reliability and wavelength independent signal phase drift is automatically compensated for.

IV. Results

Two experimental configurations based on the two different light sources previously described were used for measurements. In both cases the spectrum was filtered by a grating monochromator with a 7.2-nm spectral width. The time resolution $\Delta\tau$ on group delay measurement directly depends on the phase measurement accuracy $\Delta\phi$ and the modulation frequency f_1 through the following relationship:

$$\Delta\tau = \frac{\Delta\phi}{2\pi f_1}. \tag{12}$$

The lock-in amplifier phase resolution is 0.1°, so setting a lower bound to phase measurement accuracy.

A. Measurement Using LED's

The high spectral density of LED's enabled measurements over a large dynamic range together with the best possible phase resolution (0.1°). In order to get a higher modulation frequency we used a laser diode operating below threshold instead of a conventional LED. A source showing a LED-like spectrum together with a 300-MHz modulation capability is thus obtained. This phase accuracy and modulation frequency resulted in a 0.93-ps time resolution. Such performance allows the characterization of fibers less than 1 km in length.

On the other hand long fibers can also be measured owing to the large dynamic range obtained, as shown in Fig. 4 for a single LED source. At the peak emission wavelength a 33-dB optical dynamic range is available, so that a fiber with an equivalent loss (about 60 km) can be measured. A lower overall optical attenuation results in a wider spectral coverage. For example, measurements between 1220 and 1380 nm can be made through a 10-dB loss fiber.

The spectral coverage can be greatly extended using two optically coupled LED's as shown in Fig. 3. Measurements in such a configuration are represented in Fig. 5 for two fibers several kilometers in length. The standard step-index fiber was continuously measured between 1200 and 1640 nm thanks to its low attenuation, while the small group delay variations of the dispersion-flattened fiber show the excellent time resolution obtained. The stability and the reproducibility of the experiment were also tested by calculating the zero dispersion wavelength from 12 independent measured group delay spectra. A histogram of the results distribution is shown in Fig. 6, giving a 0.09-nm standard deviation on the zero dispersion wavelength.

B. Measurement Using a Halogen Lamp

This configuration was set up in order to test the maximum possibilities of the experiment. Such a source needs another integrated optic modulator for its high-frequency modulation. This device did not operate in the 1300-nm spectral region, because the higher order mode cutoff was about 1380 nm. The very weak detected intensity imposed a smaller signal-to-noise ratio to insure at least a 6-dB dynamic range. This results in a 0.7° maximum standard deviation on phase measurement, giving a 6.5-ps time resolution with a 300-MHz source modulation frequency.

A measurement of the same 3.8-km dispersion-flattened fiber in such an experimental configuration is shown in Fig. 7. Although the resolution is not as good as with the previous configuration, the very small group delay

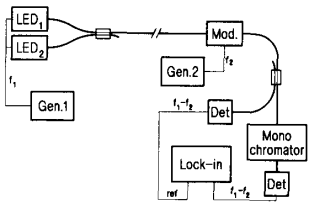

Fig. 3. Diagram of an experimental setup using the unfiltered light signal propagating through the fiber as reference signal.

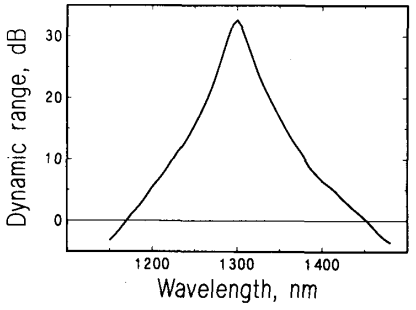

Fig. 4. Dynamic range as a function of wavelength obtained with a single LED as light source.

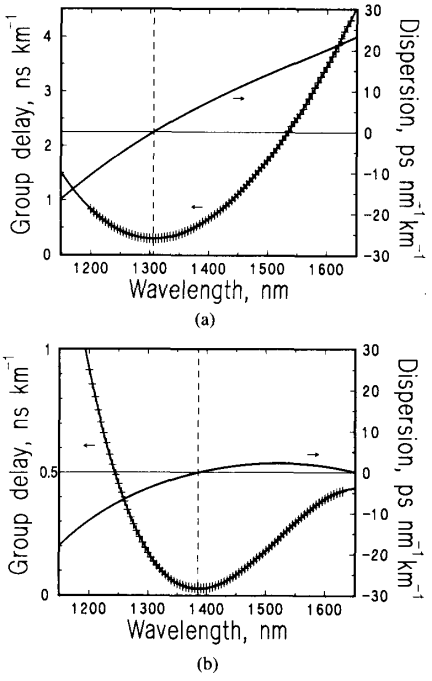

Fig. 5. Group delay spectra measured using two optically coupled LED's and fitted Sellmeier polynomials with resulting chromatic dispersion curves: (a) standard step-index fiber (L = 3.7 km), (b) dispersion-flattened fiber (L = 3.8 km).

variations recorded show that the quality of the measurement remains quite sufficient. Another fiber having a lower overall attenuation has been measured with the same setup from 1370 to 1680 nm.

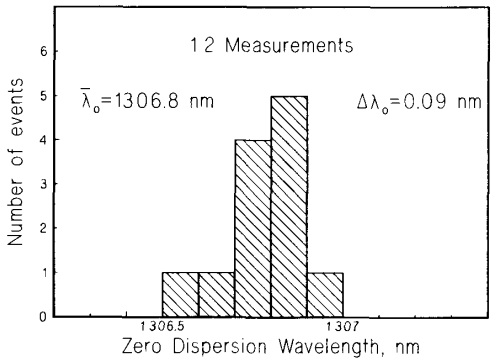

Fig. 6. Histogram of the distribution of zero dispersion wavelength calculated from independent measurements of the same fiber.

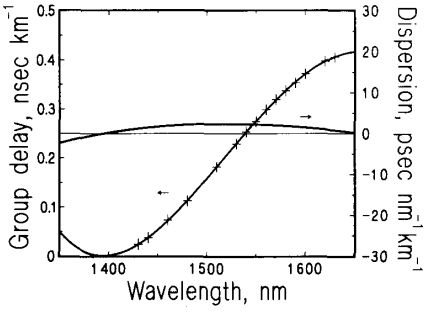

Fig. 7. Group delay spectrum of a dispersion-flattened fiber measured using a halogen lamp and fitted Sellmeier polynomial with resulting dispersion curve.

V. Conclusion

A novel experimental method was developed for group delay measurement in long single-mode fiber using a phase shift technique. The particularity of the method is the second optical intensity modulation using an integrated optics device. This modulation is located at the fiber output end, enabling photodetection and phase measurement in the low-frequency range, but with the time resolution of a high-frequency phase measurement conserved. This results in considerably improved dynamic range, spectral coverage, and immunity to electrical interference.

An experimental setup was achieved using two optically coupled LED's as light source, allowing group delay measurement with a 0.93-ps resolution over the full 1200–1600 nm spectral range. In such a configuration a 33-dB optical dynamic range is available at the peak emission wavelength. On the other hand, an experimental setup with a fully remote light source is described for measurements of installed optical links.

In addition, a configuration using a halogen lamp as light source was also achieved, demonstrating the possibility of accurately measuring chromatic dispersion in long single-mode fibers with a thermal light emission. However, the resulting small dynamic range acts as a strong limitation on potential use.

The improved measurements performed using this method should demonstrate the adequacy of polychromatic sources for dispersion characterization of single-mode fiber, a large dynamic range being obtained together with a broad continuous spectral responsivity.

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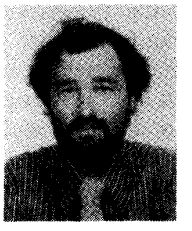

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