Review of Chromatic Dispersion Measurements Techniques

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Summary: Chromatic dispersion measurements require experimental conditions which meet with particular difficulties, that is, a wide spectral coverage and a picosecond time resolution over a kilometer-length fiber. This paper shows what makes of these measurements an experimental challenge and the main solutions found since the late seventies are reviewed. Pulse propagation, interferometric and phase-shift methods are in particular described, showing their respective advantages and limitations. Recent progresses and latest developments in the domain are then presented, such as the double optical modulation and other advanced techniques, which promise close-to-ideal conditions for this measurement in the near future.

Introduction

Chromatic dispersion results of the dependence of the propagation velocity of a mode on wavelength. It is actually caused by two different effects in a single-mode fibre: the material dispersion and the waveguide dispersion. The former is predominant and is due to the spectral variation of the refractive index of the material, which vanishes near 1300nm for silica. The latter results of the spectral variation of the fiber guiding properties. This contribution is usually small, but particular designs of refractive index profile enable the region of negligible dispersion to be shifted to the minimal attenuation window at 1550nm or even to be broadened.

The bandwidth of single-mode fiber transmission systems is ultimately limited by the chromatic dispersion, because the finite spectral width of actual optical sources results in a pulse broadening due to the different propagation time of the different spectral components of the pulse. The expected pulse broadening is given by the following expression:

$$\Delta\tau = |D| \, L \, \Delta\lambda$$

where D is the chromatic dispersion, L the fibre length and $\Delta\lambda$ the source spectral width. The measurement of chromatic dispersion is therefore of greatest importance to insure optimal performance of an optical link.

Chromatic dispersion is experimentally found out by differentiating the propagation delay – or group delay – with respect to the wavelength using a suitable numerical fitting on the measurements. Actually an ideal set-up should allow group delay measurements with picosecond resolution on a broad wavelength range (1.2-1.6 μm). This requirement makes direct delay measurements uneasy to achieve, because fast optical sources such as lasers are poorly wavelength-tunable in the spectral region of interest.

Early methods

The first practicable method for chromatic dispersion measurement, the so-called fibre Raman laser technique, was published in 1978 [1]. As most of the early findings, the method uses for the measurement what makes of the investigated phenomenon an actual limitation, that is, a different propagation time for pulses of different wavelength. The measurement technique consists in propagating narrow pulses at selectable wavelengths along the fiber and in measuring the time-of-flight variations using a sampling oscilloscope. Pulses of different wavelength are generated by the non-linear process of stimulated Raman scattering, using high peak power pulses from a pump mode-locked Nd:YAG laser injected into a single-mode fiber. Individual wavelengths are then selected using a monochromator and are launched into the test fiber, as shown in Fig.1. The shape and intensity of the pulses are strongly wavelength-dependent owing to the dispersive properties of the pumped fibre and the periodic spectral variation of the Raman scattering efficiency corresponding to integer numbers of Stokes shift. This probably results in biased measurements, so that the obtained accuracy is a few tens of picosecond with the inherent sampling oscilloscope drift and resolution. This technique has

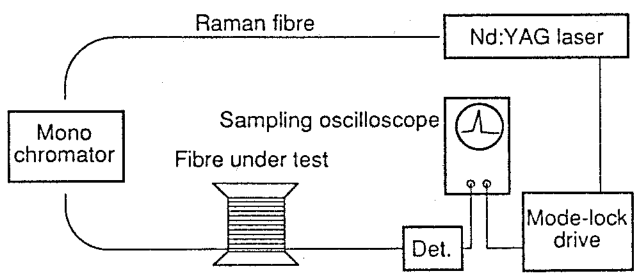

Fig.1 Schematic diagram of the fibre Raman laser method.

therefore a far from ideal resolution, but it has the advantage of an excellent spectral coverage (1.1–1.7 µm). Nevertheless it requires an expensive set-up and involves serious safety hazards, which makes it unpracticable for systematic or field controls.

In order to make the setup more portable, the fibre Raman laser can be replaced by a set of pulsed semiconductor lasers, emitting at different wavelengths and sequentially switched [2]. This actually limits the measurement to discrete wavelengths and a good spectral coverage requires a great number of lasers, leading rapidly to prohibitive costs.

Another important method is the inteferometric technique, first published in 1981 [3], which enables measurements with an excellent accuracy over widest spectral range. As shown in Fig.2 one interferometer arm consists of a reference path – either an air path or a known fibre – while the other is a meter-length sample of the test fiber. When white light filtered by a monochromator is launched into the interferometer, interferences are observed within a coherence length only when the propagation time in both the arms are equal. Group delay measurements are thus performed at each wavelength by varying the reference path length up to the position where a maximum interference visibility is observed. A compact set-up for systematic controls has been developped using an all-fiber configuration [4]. An equivalent 0.5ps/km accuracy on group delay is obtained over the full 1.0–1.7 µm spectral range. In addition the birefringence of the test fiber can be simply found out using the same experimental configuration [5]. Nevertheless this method suffers from an inherent drawback: the measurement is restricted to a meter-length sample and the extrapolating of the obtained result to the whole fiber length remains speculative.

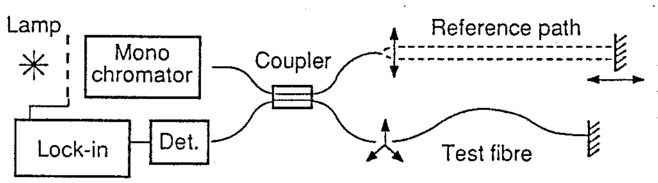

Fig.2 Schematic diagram of the interferometric method in an advanced Michelson configuration.

An important breakthrough was the development of the phase-shift technique, published in 1983 [6]. 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. The spectral scan is performed by filtering the LED spectrum by a monochromator. A schematic diagram of this technique is shown in Fig.3. The main problem arising with this method is the low intensity of the filtered light resulting in a poor signal-to-noise ratio and strong phase fluctuations. Furthermore

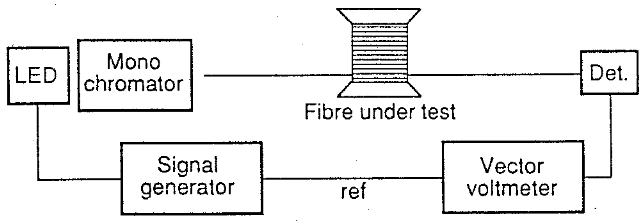

Fig.3 Schematic diagram of the phase-shift method using LED's.

radio-frequency interference due to the strong LED drive current perturbates the measured signal providing biased measurements. A 10ps time resolution can be obtained, provided that these problems are reduced by using extreme care and advanced techniques. On the other hand the LED can be replaced by an array of laser diodes, resulting in a greatly improved dynamic range, but suffering from the same formerly described drawback. Most of the commercially available measuring systems use this method today.

Latest developments

As far as measurements on long fibres are concerned, the main limitation encountered by the methods described in the previous section is due to the necessary use of a wide band detection scheme, which gives rise to a high noise level and thus a poor dynamic range. In addition the measurement is strongly perturbed and biased by radio-frequency interferences radiated by the cables. A great effort was therefore done to eliminate this drawback and the latest developments described in this section aim at performing the light detection in the low-frequency range, with the time resolution due to a high frequency modulation conserved. This condition requires additional optical processings and less direct measurements result.

Right into this way a novel phase shift technique called the double optical modulation method was recently published [7]. Its schematic diagram is shown in Fig. 4. It is basically the same configuration as a classical phase shift method, except a second intensity modulation performed at another frequency just before detection. This re-modulation splits the signal into sum- and difference-frequency components, each keeping the phase of the incident signal. Thus the time resolution remains unchanged by this

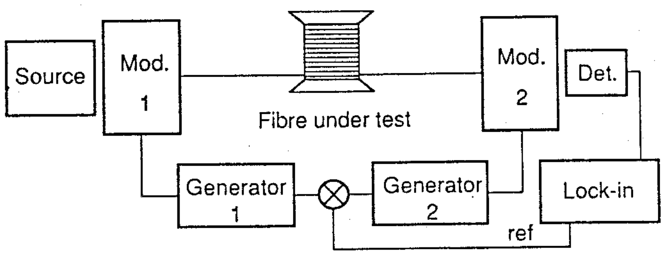

Fig.4 Schematic diagram of the double optical modulation method.

processing and the signal frequency can be arbitraly shifted this way. 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 orders of magnitude better.

The main encountered difficulty is to find suitable modulation devices operating at a high enough frequency. The first modulation can be simply performed using a LED as light source by modulating the drive current, but the second modulation requires an external device at the far fibre end. Configurations using either an acousto-optic modulator [8] or an integrated electro-optic modulator [7] were successfully tested. The latter device enables a higher modulation frequency and an all-fibre configuration to be achieved, together with a better stability and reliability. A 1ps time accuracy has been obtained over the full 1.2-1.6 µm spectral range. Fig.5 shows a

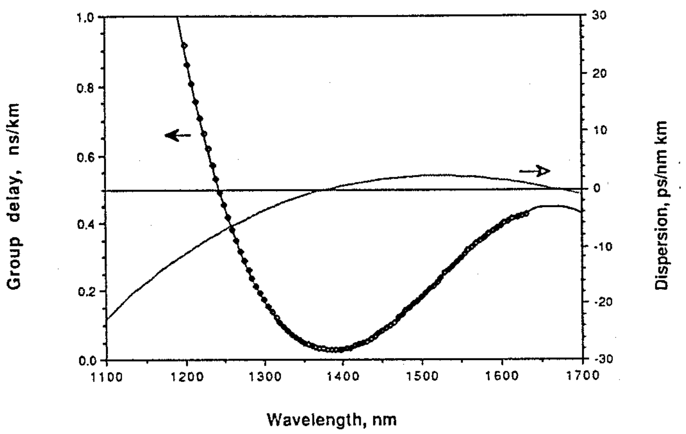

Fig.5 Group delay measurement of a dispersion-flattened fibre performed using the double optical modulation method.

measurement performed using such a set-up. Furthermore a slightly modified configuration enables the source and the detection to be fully remote [7], without requiring another link for the reference signal, so that the measurement of installed fibers can more easily performed. A measuring system based on this technique is already commercially available.

Another interesting method was also recently published [9], based on a different principle: the test fiber is placed in an interferometer in the Sagnac configuration, as shown in Fig.6, and a phase modulation using a piezo translator is performed at one end of the interferometer. When the phase modulation is resonant, that is, the propagation time through the fiber is an integer number of the modulation period, no light is transmitted at the interferometer output, because the two counterpropagating waves have an exact π phase difference. Otherwise the phase relationship between the two beams makes at least part of the light to be transmitted. The measurement consists in determining for each wavelength of a

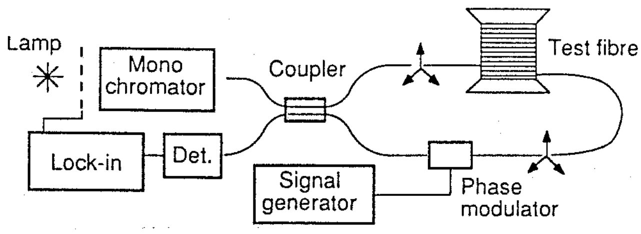

Fig.6 Schematic diagram of the resonant modulation method using a Sagnac interferometer configuration.

filtered white light source the frequency at which a minimum light is transmitted. The time accuracy is therefore only given by the resolution and stability of the signal generator driving the phase modulator. Theoretically a 1ps time accuracy can be obtained. Here again light detection is performed in the low frequency range.

Conclusion

The table below summarizes the main characteristics of the described methods

Method	Resolution	Spectral range	Dynamic range
Raman laser	50 ps	1.1–1.7 µm	
LD array	10 ps	discrete	60 dB
Phase shift	20 ps	1.2–1.6 µm	15 dB
Interferometric	1 ps/km	1.0–1.7 µm	
Double optical modul.	1 ps	1.2–1.6 µm	33 dB
Resonant modulation	1 ps ?	1.0–1.7 µm	

Recent progresses show that ideal conditions are about to be obtained, that is a 1ps time accuracy over the full spectral range of interest. The approach of the latest methods is noticeably to perform an optical processing of the signal, so that a low-frequency light detection can be used anyway.

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