Using a VCSEL to accurately measure the chromatic dispersion in single mode fibre by the phase shift technique

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Abstract – The demand for high-speed data transmission and higher bandwidth is increasing rapidly due to the growing consumer need for advanced telecommunication technology. All fibre optic cables have an inherent transmission limiting factor, known as chromatic dispersion. In this paper, a method for characterizing the chromatic dispersion in single mode fibre is described. Our approach is based on the phase shift technique, where the phase difference between two sinusoidal modulated signals is measured. A vertical cavity surface emitting laser (VCSEL) source was implemented to characterize the chromatic dispersion along different lengths of G.652, G.655 (+) and G.655 (-) single mode fibre, around the 1550 nm wavelength region. A dispersion coefficient D, between 16.5 ps/nm.km to 19.1 ps/nm.km for the G.652 single mode fibre, 2.6 ps/nm.km to 4.2 ps/nm.km for the G.655 (+) single mode fibre and -2.8 ps/nm.km to -3.2 ps/nm/km for the G.655 (-) single mode fibre was measured. The experimental results are in close agreement to those obtained in literature.

Keywords: Chromatic dispersion, phase shift technique, VCSEL.

1. Introduction

From as early as 500 B.C, when the ancient Greeks developed a telegraph system made up of beacon fires, smoke signals and mirrors, up until the early 1970’s when Corning Glass Works developed their first fibre optic cable for long haul transmission, mankind has relied heavily on communication across distance. Recent findings revealed that the gross domestic product (GDP) of a country is correlated to the development of the telecommunication infrastructure of a country [1]. The development of optical communications network systems has facilitated the growth in many areas such as, social, economic, business, education and politics [2]. Transmission speeds and fibre bandwidth capacity is limited by pulse broadening, due to the dispersive properties of an optical fibre. Chromatic dispersion is one aspect of the fibre causing an optical pulse to distort as it travels along the fibre [3]. In this paper, we experimentally demonstrated a method for measuring the chromatic dispersion in single mode fibre using a Vertical Cavity Surface Emitting Laser (VCSEL). Our technique is based on the phase shift measurement scheme. The phase shift technique has been used for the precise measurements of the optical path length and for characterizing the chromatic dispersion in multimode and single mode fibres [4].

2. Theory

The majority of all chromatic dispersion measurements in single mode fibres are obtained by determining the group delay τ_g, with respect to a specific wavelength λ. Suppose an optical signal propagating along a fibre of length l, with a group velocity expressed [2] as

$$v_g = \frac{d\omega}{d\beta} \tag{1}$$

arrives at a receiver after a certain time. The time here is referred to as the group delay τ_g, defined [2] as

$$\tau_g = \frac{l}{v_g} = l\frac{d\beta}{d\omega} \tag{2}$$

An optical signal having a spectral width of $\Delta\omega$ experiences pulse broadening since the different spectral components, with respect to distinct wavelengths propagates at different group velocities, as illustrated in figure 1. Chromatic dispersion, intramodal dispersion or group velocity dispersion (GVD) refers to the fact that the group velocity is dependent on the wavelength. The expression quantifying the spreading of the signal can be mathematically described as [2]

$$\begin{aligned} \Delta\tau_g &= \frac{d\tau_g}{d\omega} \\ &= \frac{d}{d\omega}\left(\frac{l}{v_g}\right)\Delta\omega \\ &= l\frac{d^2\beta}{d\omega^2}\Delta\omega \end{aligned} \tag{3}$$

The term $\beta_2 = \frac{d^2\beta}{d\omega^2}$ is known as the group velocity dispersion (GVD) parameter and represents the amount of broadening the pulse experiences as it propagates along the fibre [2, 5]. Since the spectral width $\Delta\omega$ is related to the linewidth of the optical source, $\Delta\lambda$, (3) can be rewritten [2] as

$$\Delta\tau_g = \frac{d}{d\lambda}\left(\frac{l}{v_g}\right)\Delta\lambda \tag{4}$$

where

$$D(\lambda) = \frac{d}{d\lambda}\left(\frac{1}{v_g}\right) \tag{5}$$

By considering (4) and (5), it follows that

$$\begin{aligned} \Delta\tau_g &= D(\lambda)\cdot l\cdot\Delta\lambda \\ \therefore D(\lambda) &= \frac{\Delta\tau_g}{l\cdot\Delta\lambda} \end{aligned} \tag{6}$$

where $D(\lambda)$ is known as the *chromatic dispersion coefficient* and expresses the broadening of the optical signal as a function of wavelength and is given in ps/nm.km [6]. The overall chromatic dispersion along a fibre of length l is mathematically expressed $D(\lambda) = D_m + D_w$, where D_m and D_w are defined as the material and waveguide dispersion, respectively. Material dispersion is attributed to the wavelength dependence on the refractive index of the optical fibre whereas waveguide dispersion in optical fibre arises as a result of the geometric shape, structural design of the optical fibre [6]. By correctly adapting the material and waveguide dispersion properties, the chromatic dispersion across the fibre length can be reduced, since material dispersion is negative in the transmission region below the zero-dispersion wavelength and positive in the wavelength region above 1.3 μm [5]. Waveguide dispersion is negative in the 1.1 μm to 1.7 μm spectrum, as illustrated in figure 2 [5]. A brief summary of the measurement techniques used for characterizing the chromatic dispersion in single mode fibre is given in table 1.

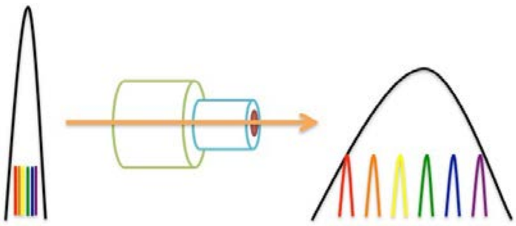


Figure 1. Pulse broadening caused by the variation in speed in the time domain.

For phase shift measurements, the change in phase $\varphi(\lambda)$ of a sinusoidal modulated signal travelling along a fibre of length l is measured due to changes in the group velocity with respect to the wavelength.

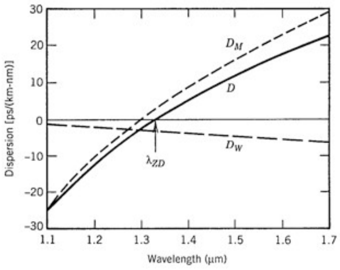


Figure 2. Material and waveguide dispersion slopes for typical single mode fibre [5].

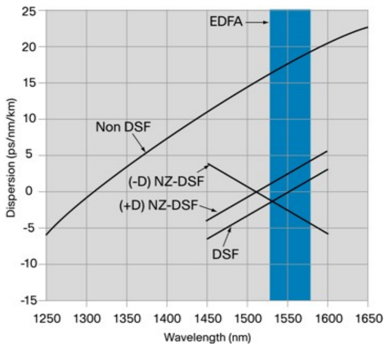


Figure 3. Chromatic dispersion slopes of the various single mode fibres [7].

Table 1. Properties of the chromatic dispersion measurement technique [8].

Measurement Technique	Measurement Resolution	Fibre length
Pulse delay/ Time-of-flight Technique	50 ps to 100 ps	Exceeding 0.5 km
Phase shift Technique	10 ps to 20 ps	Exceeding 0.5 km
Interferometric Technique	0.1 ps	Less than 5 m

The mathematical description of the phase difference is given as [9]

$$\varphi(\lambda) = 2\pi f_m \tau_g(\lambda) \quad (7)$$

where f_m is the modulation frequency. The measurement accuracy of the phase shift technique improves when considering higher modulation frequencies as well as longer fibre lengths [4].

3. Experimental Setup

Figure 4 shows the experimental configuration. A Vertical Cavity Surface Emitting Laser (VCSEL) was used for the characterization of chromatic dispersion along the single mode fibre. The directly modulated VCSEL is designed to operate in the 1545 nm to 1550 nm wavelength region. Two different types of single mode fibre were considered, the first type being G.652 standard single mode fibre.

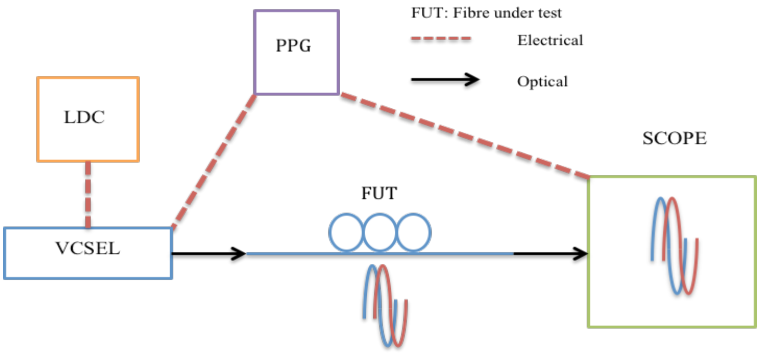


Figure 4. Schematic of the phase shift experimental setup.

The second category of single mode fibre measured was the G.655 Non-zero dispersion shifted fibre (NZDSF) positive and negative. A summary of the lengths of fibre used in the phase shift experiment is tabulated in table 2. A Laser Diode Controller (LDC) externally powered the VCSEL and by varying the bias current of LDC the wavelength of operation of the VCSELwas shifted.

Table 2. Description of the fibre lengths (km) used.

G.652 Standard Single Mode Fibre	G.655 NZDSF (+)	G.655 NZDSF (-)
6.1	26.6	25.5
11.5	51.4	
12.2	76.7	
18.3		
23.0		

A Programmable Pattern Generator (PPG) was required to sinusoidally modulate the VCSEL at a modulation frequency f_m of 8.5 GHz. The phase difference between the reference and test signals of different wavelengths was measured with a wide band oscilloscope. This particular oscilloscope has an 8.5 GHz optical channel bandwidth and a -21 dBm optical sensitivity in the 1550 nm region.

4. Results and Discussions

Figures 5 and 6 illustrate the direction of the shift occurring along the 26.6 km G.655 NZDSF (+) and 25.5 km G.655 NZDSF (-) respectively. The reference wavelength selected in both

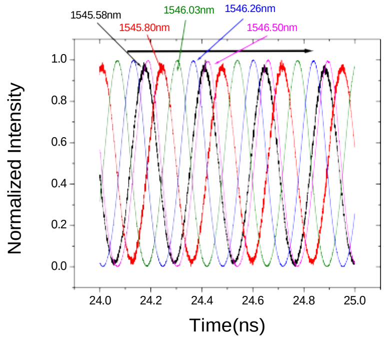


Figure 5. Phase shift along 26.6 km G.655 NZDSF (+).

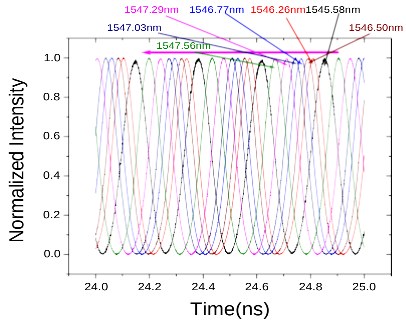


Figure 6. Phase shift along 25.5 km G.655 NZDSF (-).

instances was 1545.58 nm. From figure 5, the shift is occurring to the right of the reference signal as the wavelength is increased, whereas in figure 6 the shift occurs to the left of the reference signal with increasing wavelength. These occurrences are due the design of the optical fibre during manufacturing, where the refractive index of the fibre material is tailored in such a way as to define the sign of the chromatic dispersion along the fibre. If we consider the shift in figure 6 to be moving to the right of the reference wavelength, 1545.58 nm, as seen in figure 5. From figure 6, the sequence of wavelengths after the reference wavelength is given as 1547.56 nm, 1547.29 nm, 1547.03 nm, 1546.77 nm, 1546.50 nm and 1546.26 nm respectively. From this it can be inferred that, the longer wavelength signals travels slower along the G.655 NZDSF (-) fibre than the signals of shorter wavelength. This validates the property of the G.655 NZDSF (-), where it allows longer wavelengths to propagate slower and shorter wavelengths faster.

Figures 7 and 8 show chromatic dispersion curves measured along the G.652 standard single mode fibre and G.655 NZDSF (+) for the respective fibre lengths tabulated in table 2. An indirect approach was formulated for determining the phase difference between two signals at different wavelength, since the oscilloscope referred to in figure 4 is not capable of directly measuring and calculating phase changes. The phase difference, with reference to a specific wavelength, between sinusoidally modulated signals was calculated according to

From (8), T refers to the period of the clock signal and t_{sep} refers to the separation time between the signals, given by the oscilloscope. After calculating the phase difference it is inserted into (6), in accordance with (7). The chromatic dispersion curves for the respective lengths of G.652 and G.655 single mode fibre experimentally derived, are in good agreement with the theoretical fit as displayed in figures 7 and 8. A minor deviation from the theoretical fit was observed for the chromatic dispersion coefficient experimentally measured at the initial wavelength, in the 6.1 km G.652 SMF and in the 26.6 km and 76.7 km G.655 NZDSF (+). This observation can be attributed to the small wavelength spacing between the reference and test signal. As the wavelength spacing increased, the distance between the experimental curve and the theoretical curve reduced. Generally, the accuracy improved as the distance between the reference and test signal increased.

$$\varphi(\lambda) = \frac{2\pi \cdot t_{sep}}{T} \qquad (8)$$

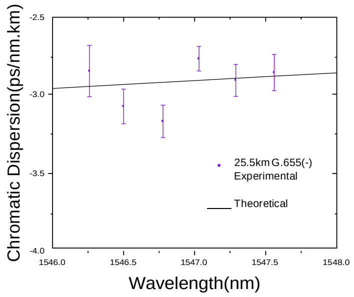
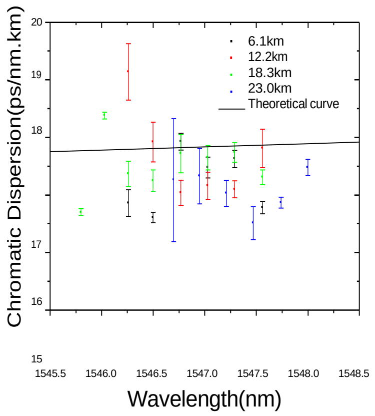


Figure 9. Chromatic dispersion spectra experimentally derived for the G.655 NZDSF (-).

A chromatic dispersion coefficient of 17.81 ps/nm.km was experimentally obtained along the 12.2 km G.652 single mode fibre as opposed to 16.78 ps/nm.km for the 6.1 km G.652 single mode fibre. These measurements were taking with respect to 1547.56 nm. This verifies the statement given in [4], that the longer fibre lengths improves the measurement accuracy of the phase shift technique. Figure 9 shows the measured chromatic dispersion data obtained for the 25.5 km G.655 NZDSF (-). The experimentally determined data is in good agreement with the theoretically calculated chromatic dispersion curve and falls within the -1.4 ps/nm.km to -4.8 ps/nm.km range stipulated by OFS Optics. The phase shift occurring in the 25.5 km G.655 NZDSF (-) illustrated in figure 6 authenticates the negative sign for the experimental data given in figure 9.



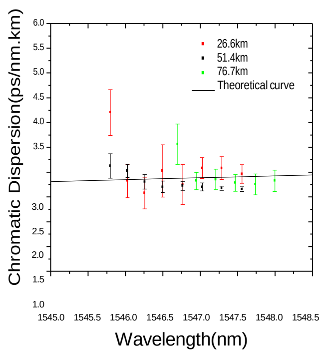


Figure 7. Dispersion curves of chromatic dispersion measurement made in G.652 standard single mode fibre.

Figure 8. Dispersion curves of chromatic dispersion measurement made in G.655 NZDSF (+).

5. Conclusion

We have successfully described an accurate system for characterizing the chromatic dispersion along any single mode fibre. The high modulation frequency selected was a major contributor to the accuracy of our phase shift technique. The results indicated that longer fibre lengths also improved the accuracy of the measurement technique. A range of fibre lengths was used for demonstrating chromatic dispersion measurements by the phase shift technique, from 6.1 km to 76.7 km. Therefore the measurement system describe in this work can used for characterizing the chromatic dispersion along the last-mile fibre network systems for FTTx application. We showed that the direction of propagation along a G.655 NZDSF (-) is opposite to the conventional forward movement of the signal in the G.655 NZDSF (+) or the G.652 standard single mode fibre. By utilizing the properties of the NZDSF (-), it is possible to achieve a total chromatic dispersion of 0 ps/nm or a value very close to 0 ps/nm across an optical fibre network system.

6. References

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