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Measuring polarization mode dispersion (PMD) in optical fibers using the nonlinear effect of four-wave mixing (FWM)

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Abstract:

Four-wave mixing (FWM) nonlinear effect is used to measure chromatic dispersion (CD) and polarization mode dispersion (PMD) spatially for different kinds of optical fiber. The back reflected signal of very high intensity pulses propagated in optical fiber is detected and one component of FWM products is used to calculate chromatic dispersion spatially. Then by controlling the state of polarization of launched light into the fiber under test, it is possible to calculate its PMD spatially.

Keywords:
Distributed chromatic dispersion, four-wave mixing, nonlinear coefficient, polarization mode dispersion

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1. Introduction:

Chromatic dispersion (CD) and polarization mode dispersion (PMD) cause spreading of transmitted optical pulses, which results in inter-symbol interference at the receiver side. Chromatic dispersion is a result of frequency dependence of refractive index of optical fibers. While polarization mode dispersion is a result of birefringence of optical fibers, which causes 1st order PMD, and frequency dependence of principal state of polarization (PSP), which causes second order PMD effect. PMD plays negligible role compared CD for data rates below 2.5 Gbps. However, its effect becomes significant as data rates reach 10 Gbps and above. PMD has to be measured before fiber links are upgraded to higher data rates [1].

The core of an optical fiber should have perfect cylindrical shape for PMD not to occur. Polarization Mode Dispersion phenomenon occurs inside optical fibers because core diameter varies slightly in a random fashion during fiber-drawing process. In addition, stress on fiber cables and environmental condition variation affect propagated light polarization evolution. Fiber core centricity deviation gives rise to modal birefringence. Modal birefringence results from slight variation of mode-propagation constant for polarized modes in x and y directions.

Physically, when an optical pulse is launched into an optical fiber at certain polarization, its polarization state changes during propagation because of the random coupling between the two polarization components. The output pulse will be broadened and distorted not only due to chromatic dispersion mechanism but also due to the effect of splitting the light pulse on two polarization components that each travels at different group velocity.

In this work, chromatic dispersion and PMD is measured spatially in optical fibers. It is crucial to measure chromatic dispersion and PMD spatially in optical fibers operated at high data rates over 10Gbps. Typically; optical fiber used in point-to-point communication links or networks is constructed from many different pieces of fibers that have different chromatic dispersion and PMD values. Measuring CD and PMD spatially along fiber links provides clear picture of dispersion map and identify fiber sections with potential large system transmission penalties. As a result, optical network designers will be able to extend reach by avoiding fibers with certain PMD or dispersion values that could hinder data transmission. Also, this scheme can be used in fiber manufacturing plant where it is possible to measure fibers' dispersion and guarantee performance.

2. Measurement setup:

Four-wave mixing (FWM) nonlinear effect is used in this work to measure spatially optical fiber dispersion. The dispersion is extracted from the detected back-reflected Rayleigh scattered signal at either the Stokes or anti-Stokes wavelengths, which has the wave-vector phase mismatch information. Therefore, one end of the fiber is required to perform dispersion measurement using this technique. The wave-vector phase mismatch signal depends on fiber dispersion, and it equals to zero when the local fiber dispersion is zero. The polarization of two continuous wave (CW) laser sources launched into Fiber Under Test (FUT) is aligned to maximize FWM products. The State Of Polarization (SOP) of launched light into the fiber is not important for dispersion measurement as long as the two wavelengths are co-polarized.

The experimental setup block diagram used for spatially resolved chromatic dispersion (SRCD) system is shown in Figure 1. The detected back reflected light measured at the output of the setup is filtered using optical bandpass filter that is adjusted at the Stokes or anti-Stokes wavelength. Then phase extracted from the processed field is used to calculate chromatic dispersion. Controlling the state of polarization of light launched into the setup would make it possible to calculate PMD of fiber under test.

The light launched into the FUT consisted of two tunable CW laser sources that are combined using 50:50 coupler, and amplified using semiconductor optical amplifier (SOA). The SOA was modulated using 1 kHz square pulses with pulse width of 1μs. An EDFA is used to amplify the pulses to peak power levels of several hundreds of mW. The laser sources are dithered using low frequency signal to avoid Stimulated Brillouin Scattering (SBS) effect in fiber under test. SOP of each of light sources was controlled using polarization controller (PC), The SOP of launched pulses into the FUT, was varied simultaneously by a third PC. The total Rayleigh a back-scattered signal from the FUT was collected using an optical circulator (C), and the Stokes component was extracted using tunable band pass filter and detected using PIN detector diode. The detected signal, which represents the wave-vector phase mismatch signal, is filtered using 500 kHz electrical lowpass filter. After digitizing the data, the chromatic dispersion map can be extracted. This setup is used as well for calculating PMD in a span of optical fiber. It is possible to summarize the processes used for the measurement and calculation of chromatic dispersion and PMD of FUT in three main stages [2].

Stage One

Launch two co-polarized optical signals as shown in Figure 2a, b to generate respective four-wave mixing product fields as shown in Figure 3 at the Stokes wavelength λ_S or the anti-Stokes wavelength λ_A sequentially in the fiber to calculate chromatic dispersion.

Stage Two

Continuously vary SOP of launched optical light sources as shown in Figure 2c using PC and calculate overall dispersion (i.e., a combination of chromatic dispersion and PMD).

Stage Three

Ideally, PMD could be calculated directly from two separate measurements by launching co-polarized light into FUT at slow and fast axes, where the difference between the calculated dispersion at both cases represents PMD. However, it is too difficult to determine the slow and fast axes of the fiber in the setup. Therefore, the measurement has to be conducted for all possible SOPs. Then, the difference between the maximum and minimum calculated dispersion of all SOP would give FUT PMD. When measuring PMD, a modification has to be done to the setup by adding PCs after the SOA to enable setting the SOP of the two CW light sources and scan across the possible SOPs to determine the right value of PMD.

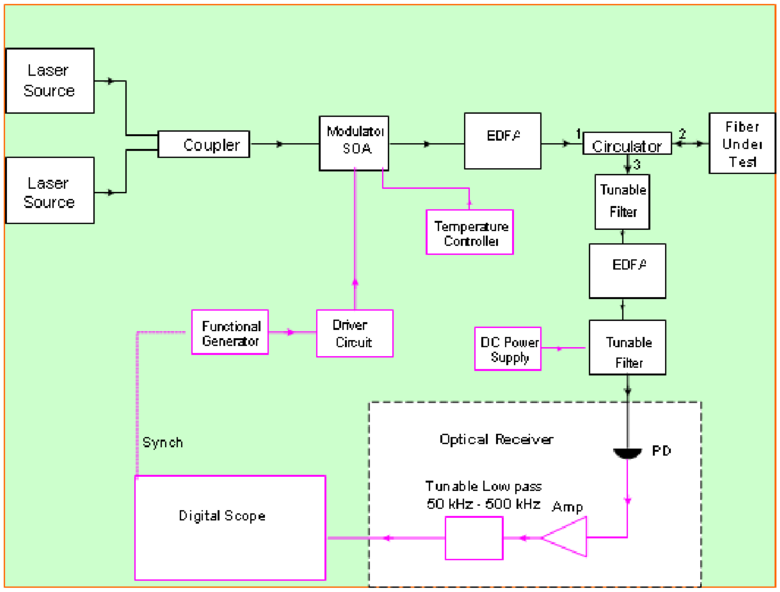

Figure (1): SRCD experimental setup block diagram

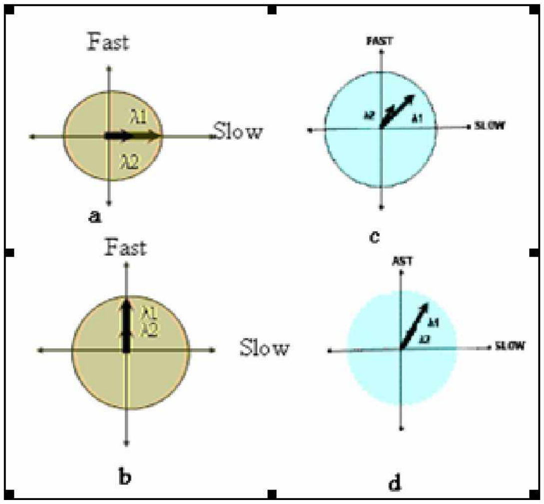

Figure (2): a, b, c and d: Graphs showing various states of polarization of input signals into the system

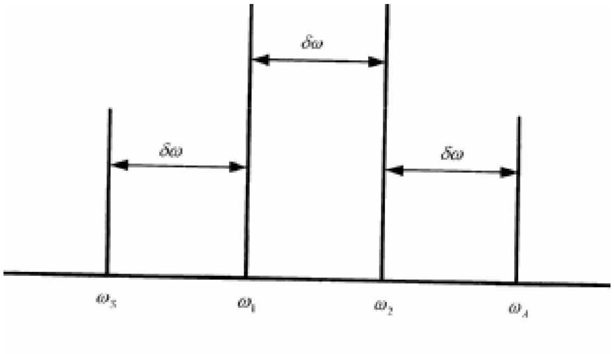

Figure (3): Graph showing the spectrum of the four-wave mixing process employed by the present setup

The following steps are used to resolve optical fiber PMD :

(a) launching into a first end of the fiber, simultaneously, a first optical signal at a first wavelength and a second optical signal at a second wavelength such that the first and second wavelength are co-polarized to generate a first probe signal using a FWM process in which two photons at the first wavelength combine with one photon at the second wavelength to eliminate nonlinear dependence of wave-vector phase mismatch signal.
(b) Measuring the frequency of oscillations of the first probe signal as a function of distance in the fiber.
(c) Deriving, for at least one of the first and second wavelengths, a chromatic dispersion parameter as a function of distance along the fiber from the measurement obtained from step (b).
(d) Launching into the first end of the fiber, simultaneously, the first optical signal at the first wavelength and the second optical signal at the second wavelength such that the first and second wavelength are at different states of polarization to generate a second probe signal using a four wave mixing process in which two photons at the first wavelength combine with one photon at the second wavelength.
(e) Measuring the frequency of oscillations of the second probe signal as a function of distance in the fiber.
(f) Repeating steps (d) and (e) at a plurality of different SOPs.
(g) Deriving, for at least one of the first and second wavelengths, a dispersion parameter representing a combination of the chromatic dispersion parameter and polarization mode dispersion as a function of distance along the fiber from the measurements obtained from steps (e) and (f).
(h) Deriving from the dispersion parameter obtained at step (g) and from the chromatic dispersion parameter obtained at step (c) the PMD in the span of optical fiber.

The measuring steps (b) and (e) are performed by observing a Rayleigh-backscattered sample of the first and second probe signals at the first end of the fiber, and the launching steps (a) and (d) comprises repetitively launching pulses at the first and second wavelengths.

3. Theory of the setup:

According to FWM theory, wavelengths λ_1 and λ_2 at various SOPs are simultaneously launched into a length of fiber under test. This will generate respective FWM product fields at the Stokes wavelength λ_S and the anti-Stokes wavelength λ_A. In order to measure distributed chromatic dispersion map, fringe period of Rayleigh back-scattered FWM signal is detected at either Stokes or anti-Stokes. The FWM signal is generated in FUT by injecting two powerful lights with frequencies ω_1 and ω_2 $(\omega_1 < \omega_2)$. Concentrating on the FWM generated from Stokes frequency $\omega_s = 2\omega_1 - \omega_2$ for simplicity, one can show that the phase mismatch Δk between the pump (ω_1) and the generated Stokes signal (ω_s) becomes [3].

$$\Delta k = -2c\pi D(\lambda_1)\left(\frac{\Delta\lambda}{\lambda_1}\right)^2 + \gamma(2P_1 - P_2) \qquad (1)$$

As the equation shows, the phase mismatching depends on the local chromatic dispersion D (linear term) and on a nonlinear coefficient γ The phase mismatch Δk leads to a temporal intensity oscillation of the Rayleigh back-scattered Stokes signal against the fiber length. Here no polarization dependent effect is taken into account. The Stokes signal can also be expressed as a spatial intensity oscillation with period λ_{sp}. This temporal oscillation frequency can be expressed as

$$f_s(t) = \frac{c}{2n}\frac{1}{\lambda_s} = \frac{c}{2n}\frac{\Delta k}{2\pi} = -\frac{c}{2n}D_c\left(\frac{\Delta\lambda}{\lambda}\right)^2 + \frac{c\gamma}{4n\pi}(2P_1 - P_2) \qquad (2)$$

Where n is the effective index of refraction of the fiber, and t is the round-trip time from the fiber input to point z and return, its defined as:

$$t = \frac{2nz}{c} \qquad (3)$$

If $(2P_1 = P_2)$ the nonlinear term is vanishing in Eq.2 and a measurement of the local frequency allows having information on the local value of the chromatic dispersion along the fiber distance. Rewriting Eq.2, the dispersion map is obtained for the first input signal at wavelength. λ_1 Defined by :

$$D(\lambda_1, z) = \frac{2n}{c^2}\left(\frac{\lambda_1}{\Delta\lambda}\right)^2 f_{sig}\left(t = \frac{2n}{c}z\right) \qquad (4)$$

Which can be rewrite as

$$D(\lambda, z) = \frac{n}{\pi c^2}\left(\frac{\lambda_1}{\Delta\lambda}\right)^2 \phi_z^{\cdot}(t) \qquad (5)$$

where *n* is the fiber refractive index, *c* is the speed of light, λ_1 is the lower wavelength CW light, $\Delta\lambda$ is the wavelength separation of the two CW light signals, and $\phi_z^{\cdot}(t)$ is the first derivative of the unwrap phase with respect to distance. [2].

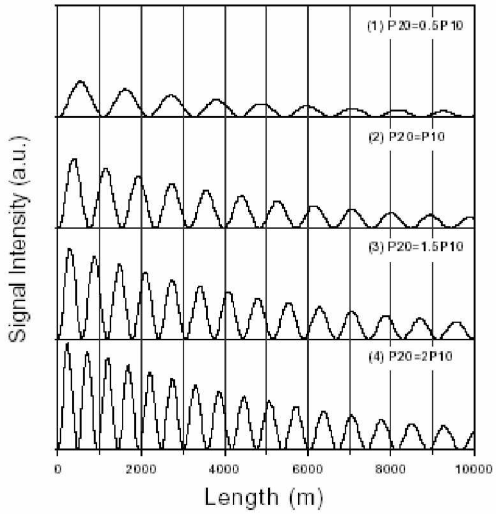

Figure (4): Four-wave mixing intensity oscillations versus fiber length for different ratio between probe and pump powers [4].

Once chromatic dispersion map $D(\lambda_1, z)$ is known and considering different ratio for pump and probe power other than two, it is possible in principle to retrieve information on the local values for nonlinear coefficient$\gamma(z)$, which will not be considered in this work.

4. Data Processing:

MATLAB software code was written using efficient Fast Fourier Transform (FFT) based algorithm to calculate dispersion from temporal oscillations. The software code has been checked against other data processing software. The approach which we used for data processing calculates dispersion and dispersion parameter as function of distance as follows:

1- Calculate FFT for all samples of detected voltage (raw data). The reflections from different distances in the FUT correspond to different beat frequencies on the detector.

2- Ignore negative frequency samples because the aim here is to get the phase of the stock signal, if both sides of FFT spectrum is used, the phase information will be lost. To clarify this idea, take a cosine signal with known frequency, when calculate FFT and perform inverse Fast Fourier Transform (IFFT), the same cosine signal is obtained, but if the negative part of the spectrum is rejected and perform IFFT a complex signal with amplitude and a phase angle $=2\pi ft$ is obtained.

3- Use lowpass and highpass filters to remove noises from the signal. The filters cutoff frequencies should be chosen based on the fiber type and length. The lowpass filter eliminates high frequency noises accompany the detected signal that originates from EDFA, multipath reflections in the fiber, filters, pin diode detector, and electrical amplifier. On the other hand, the highpass filter eliminate the DC component which is important in performing the phase unwrap to do the dispersion calculation.

4- Use positive frequency samples in inverse FFT.

5- Calculate and unwrap the phase. The phase of the detected wave-vector phase mismatch signal is calculated using the real and imaginary parts after performing IFFT. The time oscillating signal can be transformed into a circular oscillating signal by drawing the real and imaginary signals in the complex plane.

6- Calculate the dispersion map using Eq. 5.

5 Experimental results and discussion:

Different types of fibers are used in the experiments such as: dispersion compensating fiber (DCF), Non-zero dispersion shifted fiber (NZ-DSF) and Corning Single mode fiber (SMF-28 fiber).

The raw data (detected reflected signals) was collected using the setup shown is Fig, 1, and processed using in-house written software based on data processing technique mentioned above. The calculated average dispersion from spatial dispersion results is compared with dispersion measured using other commercial equipments. Commercial equipments only provide average dispersion.

Calculating Chromatic Dispersion (Stage one)

Fiber chromatic dispersion is measured for three different cases of DCF spool. First, the lunched signal is injected into one end of the fiber (forward direction). Then, the signal is injected into the other end of the fiber (reversed direction). The third case is same as the second case but repeated for different set of wavelengths. Figure 5 shows the detected wave-vector phase mismatch signal for three cases.

The time oscillating signal has an exponential decaying feature which displays fiber attenuation, while Figure 6 shows calculated FFT, Figure 7 shows unwrapped phase, and finally Figure 8 shows spatial fiber chromatic dispersion.

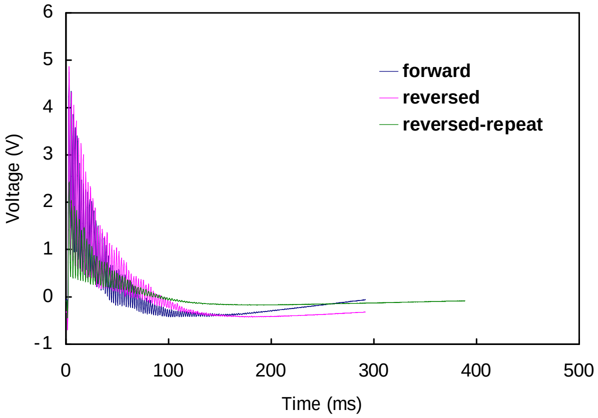

Figure (5): Time oscillating wave-vector phase mismatch signal measured for DCF

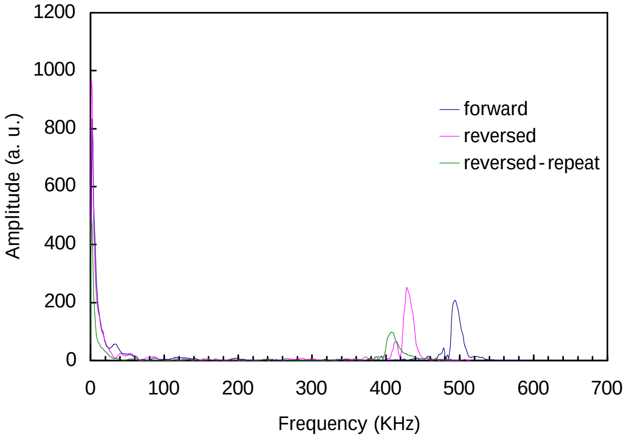

Figure (6): Fast Fourier Transform of DCF

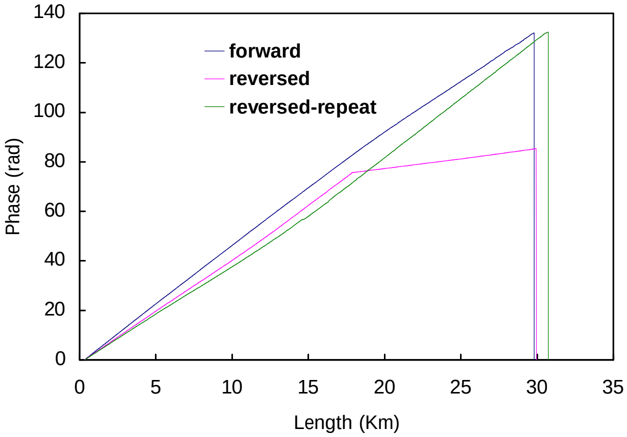

Figure (7): Unwrapped phase of DCF

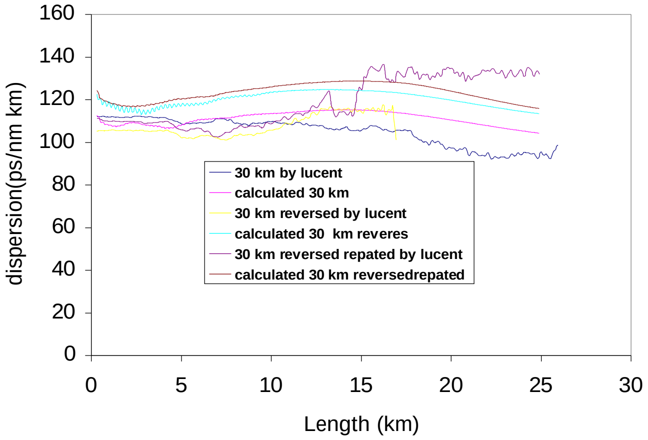

Figure (8): Dispersion of DCF

The measured dispersion for DCF is about 112 ps/km nm as shown Figure 8.

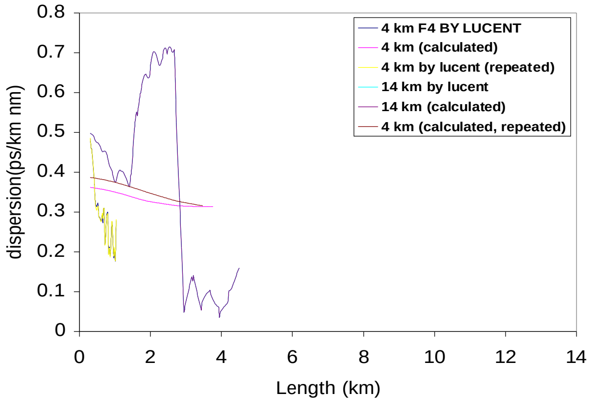

Figure (9): Dispersion in DSF

Figure 9 shows the measured dispersion for different kinds of DSF fibers. The measured average dispersion is about 0.4 ps/km nm, which is very close to known dispersion values of DSF.

Figures 10 and 11 show measured dispersion for Corning SMF-28 fiber when using different PC settings to SOF of launched laser sources.

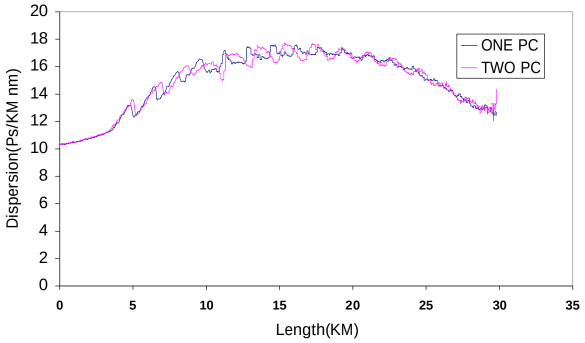

Figure (10): The overall dispersion in SMF

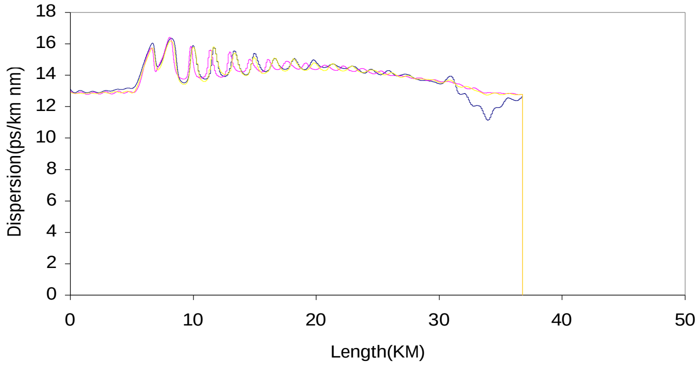

Figure (11): Dispersion in SMF

Figure 12 illustrates calculated PMD of SMF-28 fiber using spatial chromatic dispersion setup. The calculated PMD is about 0.45 ps.

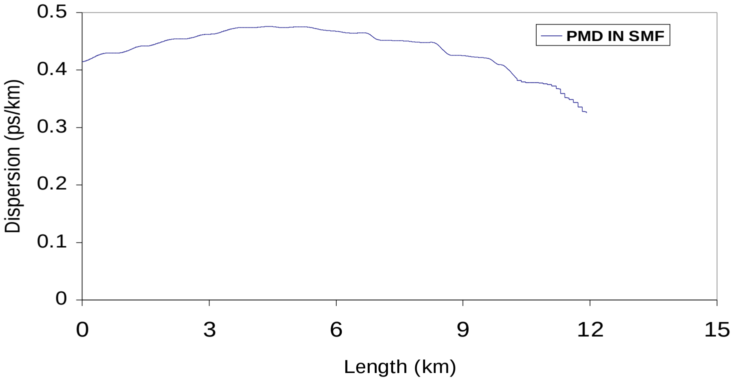

Figure (12): PMD in single mode fiber

6. Conclusions:

Novel setup is used for measuring CD and PMD spatially. The proposed technique measures CD and PMD spatially based on extracting wave-vector phase mismatch signal generated by FWM of two CW light sources propagated through fiber under test. The strength of the Stokes and anti-Stokes signal depends on the fiber dispersion, which equals to zero when the local fiber dispersion is zero. On the other hand, the strength of the generated FWM components is inversely proportional to $\Delta\lambda$ (the wavelength separation between the two sources). When the fiber dispersion is high in optical fibers such as SMF-28, $\Delta\lambda$ has to be small (~0.6 nm), while it could be as high as 3.6 nm for DSF, and NZ-DSF. This can be attributed to the efficiency of FWM nonlinear effect, which is higher at wavelengths close to the zero dispersion wavelength of the fiber. Therefore, the combination of both $\Delta\lambda$ and the CW sources wavelength have to be taken into account when performing the dispersion measurement. The SOP of the light launched into the fiber under test is not important in the dispersion measurement as long as the two wavelengths used in the measurement are co-polarized on one of the polarization axis.

References:

[1] Agarwal. D.C, (1993), “Fiber optic communication, 2nd edition,” Wheeler Publishing.

[2] Atieh. Ahmad. K, Liang. Yi Woodside and Shane H, (2001), “System and method for resolving polarization mode dispersion in optical fibers,” US patent no. 6,462,863.

[3] Cho .P. S, Grigoryan,V. S. N, Reingand, and I. Shpantzer,(2001), “Optical differential binary phase shift keying of return-to-zero pulses for long-haul DWDM transmission systems,” IEEE Photonics Technology Letters, 17(1), pp. 176-180.

[4] Aso .Osamu, Masateru .Tadakuma and Shu. Namiki,(2000), “Four-Wave Mixing in Optical Fibers and Its Applications,” Furukawa Review, No. 19.