EFFECTS OF TEMPERATURE ON POLARIZATION MODE DISPERSION OF G.652 OPTICAL FIBERS

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Abstract- In current high bit rate long haul transmission systems, PMD is the most important factor causing degradation in system performance. Therefore PMD compensation is an important subject for reliable high bit rate transmission systems. PMD compensation techniques require information about effects of environmental conditions on PMD. In this paper, effects of temperature on PMD performance of G.652 standard communications fiber manufactured according to TRFO-9b Optical Fiber Cable Specification of Turkish Telecom are reported. Results show that in the adiabatic regime, the ratio of the standard deviation to the mean value, which is experimentally obtained as 0.39, is in good agreement with the theoretical value obtained as 0.42 from Maxwellian distribution while in the isothermal regime the experimental ratio obtained as 0.14 is far from the theoretical ratio. Furthermore, in the adiabatic regime mean PMD slightly varies with the wavelength while in the isothermal regime variation of PMD with the wavelength is significant and shows a strong oscillation. In the isothermal regime, a temperature sensitivity of $\pm$ %19 /°C is also obtained. The results can be used in developing a PMD compensation method for communication systems based on the optical fiber type used in this research.

I. INTRODUCTION

Dispersion is the main factor limiting the transmission capacity of optical fiber communication systems by causing inter-symbol interference (ISI) and increasing bit error rate (BER) of the system. Two types of dispersion called as chromatic dispersion and polarization mode dispersion (PMD) occur in single mode optical fibers. Chromatic dispersion is due to the wavelength dependence of the speed of light transmitted in the optical fiber. Chromatic dispersion is composed of material dispersion and waveguide dispersion. Material and waveguide dispersions can be positive or negative and they can even cancel each other. Furthermore, there are various methods compensating chromatic dispersion effects in high bit rate long haul communication systems [1-3]. Therefore, although chromatic dispersion has higher values than PMD, it can be compensated more easily. PMD is a statistical effect depending on the two orthogonal modes transmitted instead of a single mode in circular symmetric single mode fibers. Currently, PMD is the most important factor affecting the pulse broadening and power degradation in optical fiber communication systems operating over transmission rates of 5 Gbps. Therefore, it must be reduced to achieve a reliable high bit rate communication. For installed high-PMD fibers, several PMD compensation methods have been proposed [4-7]. However, compensation methods usually require information about effects of environmental conditions on PMD performance of communication systems.

In previous works, effects of mechanical conditions such as tension, compression, torsion, bending and flexing as well as environmental conditions such as vibration and temperature on the PMD performance of optical fiber ribbons were reported [8-11]. In this paper, experimental results about the effects of temperature on PMD performance of G.652 standard communications fiber manufactured according to TRFO-9b Optical Fiber Cable Specification of Turkish Telecom are reported. Experiments have been performed both in the adiabatic and isothermal regime and the experimental data are compared with the theoretical data. The results can be used to develop a PMD compensation method for communication systems based on G.652 communications fibers.

In the second section, theoretical background of PMD is described. In the third section, experimental methods, devices and conditions are given. In the fourth and fifth sections, experimental results in the adiabatic and isothermal regimes are presented respectively and interpreted.

II. THEORETICAL BACKGROUND OF PMD

In G.652 communication fibers, two main factors contributing to PMD generation are perturbations on the circular geometry of the fiber and internal stresses causing anisotropy in refractive indices. Other factors can be listed as bendings, twists and manufacturing process. These effects cause local birefringence. Birefringence is also related to polarization mode coupling. Polarization mode coupling can occur continuously and randomly in single mode fibers. Under constant coupling conditions two polarization modes exist. These modes are orthogonal and called as principal states of polarization or shortly PSP. PSPs form fast and slow birefringence axes for a homogeneously birefringent fiber segment. To understand the existence of PMD on optical fibers, a short homogeneously birefringent segment of a long fiber should be initially analyzed. A single mode fiber can be modelled as a concatenation of various randomly birefringent fiber segments.

The birefringence in optical fibers can be described as variations in the refractive indices. Then, the variation between the propagation constants of orthogonally polarized modes can be written as

$$\Delta\beta = \beta_s - \beta_f = \frac{\omega n_s}{c} - \frac{\omega n_f}{c} = \frac{\omega \Delta n}{c} = \frac{2\pi}{\lambda}\Delta n \qquad (1)$$

where β_s and β_f denote the propagation constants of slow and fast axes, respectively, ω denotes the angular frequency of light, c denotes the speed of light in vacuum, n_s and n_f denote refractive indices on slow and fast axes, respectively, $\Delta n = n_s - n_f > 0$ denotes the refractive index variation between slow and fast axes, λ denotes the wavelength of light in vacuum. The birefringence can alter the state of polarization, i.e. SOP, of light propagating in the fiber. Each polarization state can be decomposed to PSPs that are not affected by birefringence. The phase delay between two orthogonal modes due to the birefringence causes periodical variations in polarization. Generally, a delay in the group velocity accompanies to the phase delay and separations occur among pulses propagating along the fiber. This delay between group velocities is called differential group delay, or shortly DGD and denoted by $\Delta\tau$. By taking the derivatives of propagation constants in (1) with respect to the frequency, DGD can be obtained as

$$\Delta\tau = \frac{L}{\Delta v_g} = \frac{d\Delta B}{d\omega}L = \left(\frac{\Delta n}{c} + \frac{\omega}{c}\frac{d\Delta n}{d\omega}\right)L \qquad (2)$$

where Δv_g is the group velocity variation between orthogonal modes and L is the fiber length. The value $\Delta\tau/L$ is mentioned in terms of ps/km in short fiber segments while it is proportional to the square root of the fiber length in long fibers.

Theoretically, the differential group delay $\Delta\tau$ of a single mode fiber comprising various randomly birefringent segments shows a Maxwellian distribution. That is, the normalized probability density function PDF can be expressed as

$$f\left(x, \langle\Delta\tau\rangle\right) = \frac{32.x^2}{\pi^2\langle\Delta\tau\rangle^3}\exp\left(-\frac{4.x^2}{\pi\langle\Delta\tau\rangle^2}\right) \qquad (3)$$

where $\langle\Delta\tau\rangle$ is the mean differential group delay and $x=\Delta\tau/\langle\Delta\tau\rangle$ [12, 13].

Maxwellian distribution is a result of statistics related to the local birefringence and shows the dependence of PDF to the fiber model used. The physical meaning of the statistical distribution function is the DGD distribution being a function of wavelength, time and environmental effects.

The mean differential group delay $\langle\Delta\tau\rangle$ in (3) can be computed with (4)

$$\langle\Delta\tau\rangle = D_{PMD}\sqrt{L} \qquad (4)$$

where D_{PMD} is the PMD coefficient mentioned in terms of $ps/\sqrt{km}$ and L is the fiber length.

III. EXPERIMENTAL METHODS DEVICES AND CONDITIONS

The effects of temperature on PMD should be investigated in two different regimes, i.e. isothermal and adiabatic regimes. In the isothermal regime, the temperature is constant and internal stresses of optical fibers approach to the steady state values. Adiabatic regime is the case where internal stresses vary in time with temperature variations.

Table 1. Technical properties of G.652 communication fibers used in experiments

Parameter	Value
Chromatic dispersion (1285-1330 nm)	≤ 3.5 ps/nm.km
Chromatic dispersion (1525-1575 nm)	≤ 17 ps/nm.km
Mode field diameter (1310 nm)	(8.6-9.5) ± 0.7 μm
Cladding diameter	125 ± 1.0 μm
Core/cladding concentricity error	≤ 0.8 μm
Cladding non-circularity	≤ 2.0 %

Table 2. PMD characteristics of G.652 communication fibers used in experiments

Fiber	Mean PMD (ps)	PMD coefficient ($ps/km^{1/2}$)	Length (km)
A	0.49	0.11	20
B	4.56	1.02	20

PMD behavior of G.652 standard communication fiber has been experimentally investigated in both adiabatic and isothermal regimes by using a Jones matrix method based PMD/PDL analyzer operating at 1510-1560 nm wavelength range and Agilent 81680A tunable laser. In the isothermal regime, experiments have been performed at different temperature values such as 10 ± 0.5 °C, 25 ± 0. 5 °C, 45 ± 0.5 °C ve 48 ± 0.5 °C. In adiabatic experiments, the temperature has been increased from 10 °C to 60 °C with a rate of 4 °C/h. Then the temperature has been decreased to 10 °C and it has been kept constant for 6 hours before starting a new cycle. The fibers used in experiments are two G.652 standard communication fibers manufactured according to TRFO-9b Optical Fiber Cable Specification of Turkish Telecom and wound on wooden drums. The technical properties and PMD characteristics of these fibers are given in Table 1 and Table 2, respectively [14].

IV. EXPERIMENTAL RESULTS IN THE ADIABATIC REGIME

PMD distribution of fiber B in the adiabatic regime obtained by performing 4750 measurements is shown in Fig. 1. The x-axis of the distribution graphic is the cumulative probability derived from Maxwellian function.

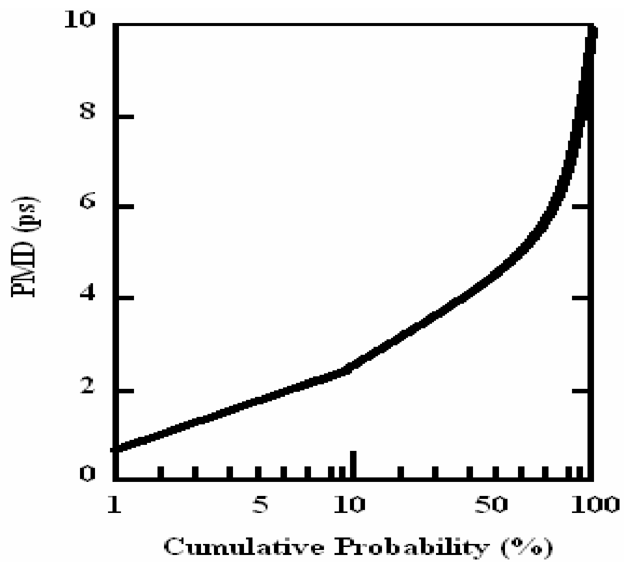

Fig. 1. PMD distribution of fiber B in the adiabatic regime

As shown in Fig. 1, PMD distribution of fiber B obtained under adiabatic conditions is in good agreement with theoretical Maxwellian distribution. The mean and standard deviation values obtained in experiments are 4.56 ps and 1.78 ps, respectively. The ratio of standard deviation to the mean value is 0.39 and it is in good agreement with the theoretical ratio obtained as 0.42.

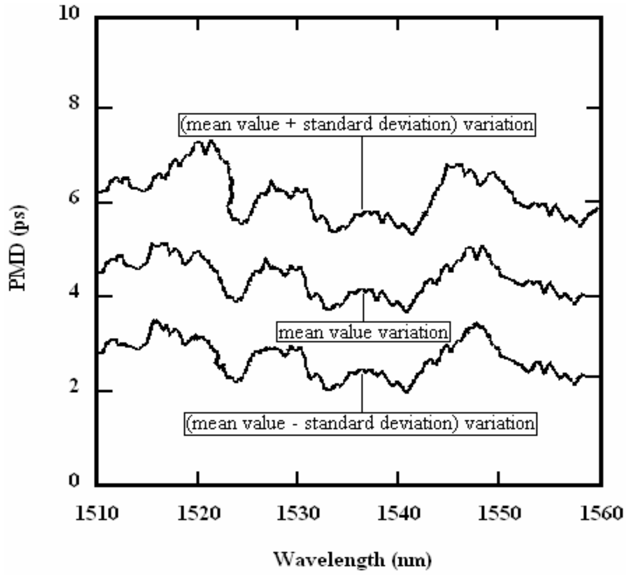

Fig. 2. PMD wavelength spectrum of fiber B in the adiabatic regime

The variation of PMD with the wavelength in the adiabatic regime is shown in Fig. 2, where mean value, mean value + standard deviation and mean value – standard deviation plots are given as functions of wavelength. The mean PMD value and the ratio of the standard deviation to the mean value slightly vary with the wavelength.

V. EXPERIMENTAL RESULTS IN THE ISOTHERMAL REGIME

PMD distribution of fiber B at 25 ± 0.5 °C ambient temperature obtained by 4750 measurements is shown in Fig 3. Measurements have been repeated every two hours for a total testing time of 532 hours.

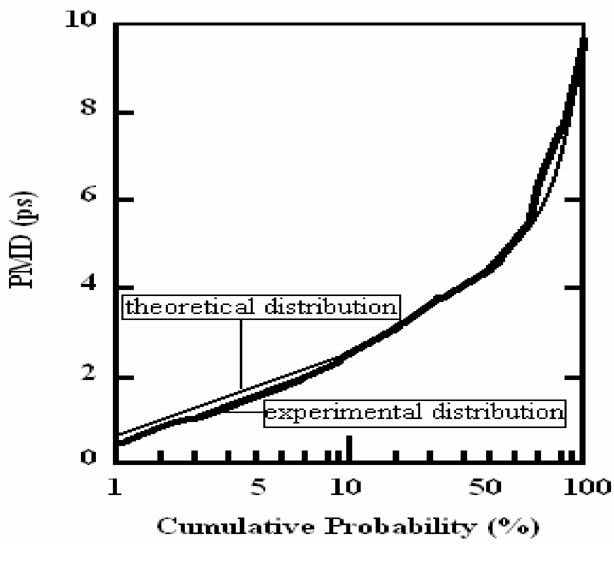

Fig. 3. PMD distribution of fiber B in the isothermal regime

Comparing the adiabatic and isothermal PMD distributions in Fig. 1 and Fig. 3, it is obvious that adiabatic distribution is in good agreement with the Maxwellian function while isothermal distribution deviates from the Maxwellian function at ranges 0.8-2.3 ps and 5.5-7.6 ps.

PMD wavelength spectra of fiber B under isothermal conditions at 25 °C is shown in Fig. 4 for mean value, mean value + standard deviation and mean value – standard deviation. As shown in Fig 4, in the isothermal regime and at fixed wavelength, PMD standard deviation is a small fraction of the mean value. The ratio of the standard deviation to the mean value at fixed wavelength is obtained as 0.14, which is a significantly smaller value than the theoretical value of 0.42. Therefore, at fixed wavelength and in the isothermal regime, PMD distribution plotted as a function of time will deviate from the Maxwellian function. Furthermore, variation of mean PMD with the wavelength under isothermal conditions is significantly larger than that under adiabatic conditions and shows a strong oscillation.

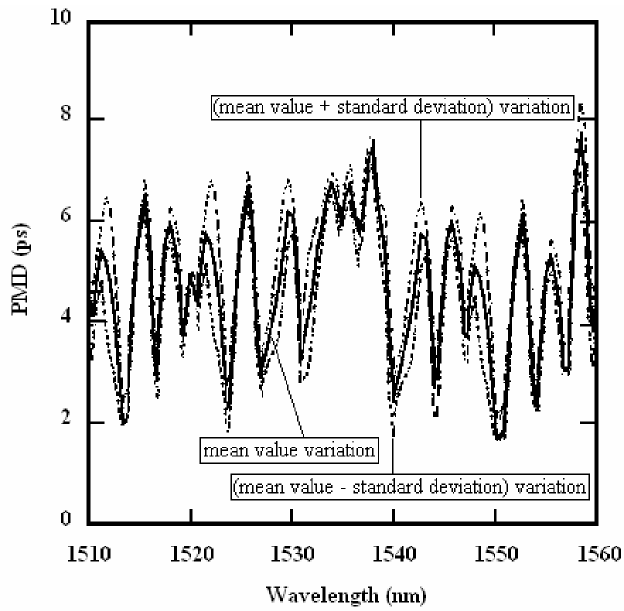

Fig. 4. PMD wavelength spectrum of fiber B in the isothermal regime

To obtain the temperature dependence of PMD at fixed wavelength, isothermal temperature increment should be kept so small that PMD variations will be monotonic. Mean PMD values of fiber A, whose PMD characteristics are given in Table 2, obtained at 45 °C and 48 °C after a total experimental time of 72 hours are shown in Fig. 5.

It is obvious in Fig. 5 that PMD has significant temperature dependence under isothermal conditions. This temperature sensitivity is determined with the parameter $\left[1/\tau(\lambda)\right]\partial\tau(\lambda)/\partial T$, where $\tau(\lambda)$ is the PMD at a fixed wavelength and T is the temperature. For the data given in Fig. 5, the average value of this parameter over the whole wavelength range is close to zero. However, around the mean value, there is a distribution whose rms value is %19/°C. Therefore, a temperature sensitivity of 0 ± %19 /°C exists.

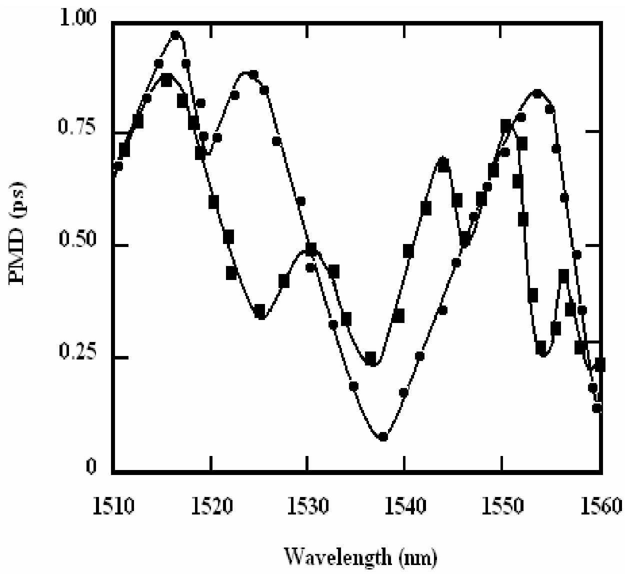

Fig. 5. PMD wavelength spectrum of fiber A at 45 °C (the curve marked with circles) and 48 °C (the curve marked with squares)

Considering that PMD values of fiber A are much lower than that of fiber B in Table 2, it is obvious that fiber B has stronger temperature sensitivity.

VI. CONCLUSION

In this paper, temperature effects on PMD of G.652 communications fiber are investigated in both adiabatic and isothermal regimes. In the adiabatic regime experimental PMD distribution shows a good agreement with the theoretical Maxwellian distribution function. The ratio of standard deviation to the mean value obtained as 0.39 is also very close to the theoretical value of 0.42. A slight wavelength dependence is also found in the PMD spectrum under adiabatic conditions. Under isothermal conditions, a significant wavelength dependence is found in the PMD spectrum. Experimental PMD distribution in the isothermal regime deviates from theoretical Maxwellian distribution especially at ranges 0.8-2.3 ps and 5.5-7.6 ps. Furthermore, the ratio of standard deviation to the mean value obtained as 0.14 is far from the theoretical value. The experiments indicate that PMD is sensitive to the ambient temperature. A temperature sensitivity of 0 ± %19 /°C is found. Therefore, it can be concluded that fluctuations in isothermal PMD at fixed wavelength are due to variations at the ambient temperature. The amount of fluctuation depends on both the magnitude of the temperature change and the sensitivity of PMD to temperature.

The experimental results reported in this paper can be used in developing a PMD compensation method for communication systems based on G.652 fibers. In particular, adiabatic results can be used for systems being exposed to high daily temperature changes while isothermal results can be used for PMD compensation of submarine cable systems.

ABBREVIATIONS

BER - Bit Error Rate

DGD - Differential Group Delay

ISI - Inter-symbol Interference

PDF - Probability Density Function

PMD - Polarization Mode Dispersion

PSP - Principal States of Polarization

SOP - State of Polarization

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