OPTICAL FIBER POLARIZATION MODE DISPERSION FOR 40 Gbit/s TRANS-OCEANIC TRANSMISSION SYSTEMS

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ABSTRACT

This paper focuses on the issues that have to be considered in order to manufacture fibers and cables with very low polarization mode dispersion (PMD) levels. We will discuss process control, optimized fiber spinning, and the measurement of the fiber PMD. The intrinsic fiber PMD can only be effectively evaluated using the low mode coupling (LMC) PMD measurement technique. We show that proper process control, driven by LMC PMD measurements, has facilitated the production of a large volume of submarine cable with record low PMD, sufficient to support transmission rates of 40 Gbit/s at trans-oceanic distances.

1. INTRODUCTION

40 Gbit/s transmission rates have become widespread in terrestrial backbone networks, and employing similar bit rates in submarine links may seem a logical step to allow seamless integration between terrestrial and submarine networks.

Coherent detection schemes with digital signal processing that are robust to PMD may, at some time, make the requirement for low PMD fibers less critical, but for 40 Gbit/s systems that are being deployed now and in the near future, and for upgrades from 10 to 40 Gbit/s, low PMD fibers are a requirement for long transmission distances.

The ITU-T standards for PMD on terrestrial fiber cables cannot be used as guidelines for the necessary PMD levels. The link requirements are aimed at 10 Gbit/s in terrestrial networks and are not sufficient to guarantee transmission of 40 Gbit/s over trans-oceanic distances[1]. The ITU-T focuses on a fairly limited number of fibers in the transmission line, employing the term Link design value LDV [17], for evaluating the risk of a few outliers that may jeopardize a fairly short link. For submarine transmission lines over several thousands of kilometers the average PMD number is a more appropriate description.

PMD can, to some extent, be compensated. This of course would cause added cost and complexity at the terminals, and only PMD levels up to 30 to 40 % of the bit slot can be tolerated, depending on the modulation format.

2.LOW PMD FIBER MANUFACTURING

The Differential Group Delay (DGD) is a measure of the difference in propagation delay of the two polarization modes of an optical signal. In a fiber, the differential group delay is a varying function of wavelength due to mode coupling between the two polarization modes. Any change in the environment, e.g. as an installed fiber will experience due to change in temperature or physical movement of the fiber, will change the mode coupling and thus change the DGD. Therefore DGD is a statistical quantity. However, it can be shown that 1) the DGD distribution that results from environmental variations is the same as the DGD distribution as a function of wavelength, if the environmental changes do not change the statistics of the mode coupling, and 2) the DGD values follow a Maxwell distribution, which is completely determined by its average value[2]. The PMD value is defined as the wavelength average of the DGD. The overall PMD dependence on length, z , is given by [3]

$$\mathrm{PMD}(z) = \frac{8L_C}{\omega L_B}\sqrt{\frac{\pi}{3}}\left[\exp(-z/L_C) + z/L_C - 1\right]^{1/2} \qquad (1)$$

Where $L_B = 2\pi/\delta\beta$ is the beat length equivalent to the total birefringence, $\delta\beta$, and L_C is the correlation length of the birefringence. For long lengths of fiber, longer than the correlation length, the PMD is proportional to the square root of the fiber length.

The causes of PMD in a fiber can be divided into two categories: those that are caused by the intrinsic birefringence and those due to external effects. The asymmetries introduced into the fiber during the preform manufacturing and fiber drawing, are well known to give form-induced and stress-induced birefringence [3]. The external perturbations such as lateral forces from fiber winding, asymmetric coating or coloring, add stress components to the birefringence and a change in mode coupling. The fiber manufacturing process can impact both. It is therefore of paramount importance to have a process control scheme that is able to catch all the important PMD contributors [4].

2.1 SPUN FIBERS

The intrinsic DGD level can be reduced by introducing an axial spin in the fiber when it is being drawn [5]. An effective method for obtaining a frozen-in spin, invented by Hart *et al* [6], is to induce torsion on the fiber after the coating application that causes the fiber to rotate in the molten phase of the draw neck-down region. By varying the torsion as a function of time, different spin functions can be built into the fiber [7]. The spinning rotates the fiber birefringence along the fiber. An example of a spin function, $A(z)$, is a sinusoidal spin, $A(z) = A_0 \sin(2\pi z/p)$, with period p and amplitude A_0 (in radians). At rapid spin rates the evolution of state of polarization (SOP) is slowed down, leading to a reduced DGD [8]. The effectiveness of a certain spin can be judged by the spin reduction factor (SRF), which is the ratio of the DGDs in the spun and un-spun fiber. For certain spin parameters, so-called phase-matching conditions can theoretically be achieved, where SRF is equal to zero [9, 10], i.e. total elimination of PMD. In practice, however, the SRF will be limited by the finite correlation length [11], and similarly by small, random deviations from the optimum spin profile [12].

2.2 FIBER PMD EVALUATION

Historically the PMD of a fiber, as measured on the shipping spool, has often been referred to as the fiber PMD. However, as illustrated in figure 1, measuring the PMD on the fiber on a spool does not give a reliable estimate for PMD when the fiber is deployed. Typically, spooled fibers will have fairly high winding tension to allow shipping and unwinding the fiber from the spool. This tension, and the resulting axial perturbations that occur at the fiber cross-overs within the package, will create mode coupling which may reduce the measured PMD. The winding diameter on the shipping spool will also lead to bending induced PMD, which can be a significant part of the measured PMD value of low PMD fibers.

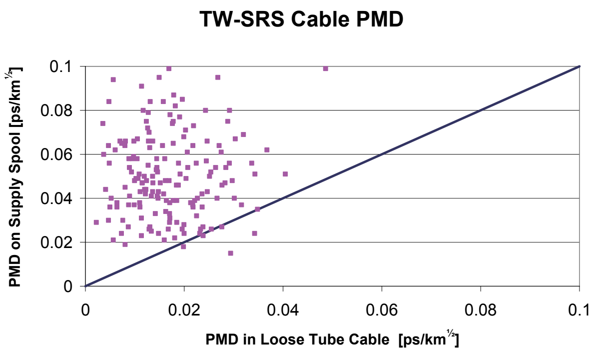

Fig. 1. Comparison between PMD as measured on the supply spool and PMD in the cable. There is no correlation between the two due to the winding tension and the bend diameter of the fiber on the spool. It is worth noting though that almost all spool PMD values are higher than the cabled PMD.

Evaluating PMD during fiber production is done by measuring the PMD of samples of fiber wound in what is called the Low Mode

Coupling (LMC) configuration. In the LMC measurements, 1000 m of fiber is placed in a loose coil with a 320 mm diameter. The bend radii is thus in excess of the 150 mm minimum proposed by IEC [13]. Interactions between the different windings in the coil are minimized by applying talcum powder. Several samples along each preform can easily be measured and thereby verify the low fiber PMD along the length of a preform. The Jones Matrix Eigenanalysis measurement technique with a 120 nm bandwidth is used to measure the very low PMD levels. The fiber sampling scheme may depend on the fiber preform size and intrinsic PMD.
The LMC measurement is aimed at evaluating the intrinsic PMD of the fiber and is not useful for finding sources of PMD like localized defects. For this, other process controls are necessary.

2.3 FIBER TYPES
For medium haul distances, negative dispersion NZDF fibers, like OFS' TrueWave® submarine fibers, often provide the most economical solution. These are deployed as either single fiber-type spans, e.g., comprised of only TrueWave Submarine Reduced Slope (TW-SRS) fiber, or as hybrid spans with a large effective area fiber, e.g., TrueWave®XL (TW-XL), near the amplifier, followed by the TW-SRS fiber in the second half of a repeater span. Dispersion is then partly compensated every 8-10 spans, with single mode fibers of either the G.652 type, e.g., AllWave® or G.654 type, e.g., Super Large effective Area (SLA) fiber. Full dispersion compensation is only possible at one wavelength as all these fiber types have positive dispersion slopes.
For trans-oceanic distances, slope matched fibers like OFS UltraWave™ fiber sets are used [14]. Slope matched spans are comprised of a pair of fibers with complementary properties. When the fibers are combined the accumulated dispersion and dispersion slope are completely compensated and the span-average Aeff is large so that nonlinear propagation impairments are minimized. The SLA fiber, with very high effective area, is placed just after the repeater. The smaller effective area IDF™, (Inverse Dispersion Fiber), that compensates both dispersion and dispersion slope of the SLA fiber over the full C-band, is placed in the span after the SLA, where the optical power is low.
To achieve the negative dispersion and dispersion slope the IDF type fiber has a fairly complicated index profile with a high index core ΔN and a small diameter, which makes the fiber birefringence much more sensitive to core non-circularity, nc [3].

$$PMD \sim \Delta N^2 * nc$$

Using this formula to evaluate the sensitivity of the fiber design indicates that IDF fibers are almost ten times more sensitive to core non-circularity than G652 SSMF.

3. PMD IN SUBMARINE CABLES

Submarine cables for repeatered links are in general designed with a central gel-filled loose tube, protected by steel strength members and an outer polymer sheath. Further, temperatures in the installed environment are in general very stable, and the expected external perturbations are minimal. This is a very benign environment for the optical fibers with little external stress.

NZDF fibers for submarine cables have undergone the same continuous improvement in PMD as terrestrial NZDF fibers[15] achieving average PMD levels around 0.02 ps/√km. Shown below are LMC fiber and cabled fiber PMD distributions of the two types of negative dispersion NZDF fibers that are used in short and medium haul systems, as well as the G652D compensating fibers that were used in the same deployment.
The cable data are for OFS fibers after they have been manufactured into the Tyco Telecommunication's SL® cable design. The inserts in the figures give the distributions of the LMC PMD measurements associated with

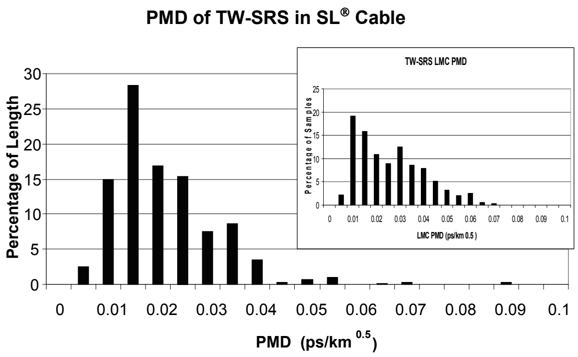

Fig.4. PMD of approximately 13,700 km of TW-SRS fiber in the SL® cable. The RMS average cable PMD is 0.021 ps/km$^{0.5}$. The insert shows the LMC PMD distribution of these TW-SRS fibers. The average LMC PMD is 0.022 ps/km$^{0.5}$.

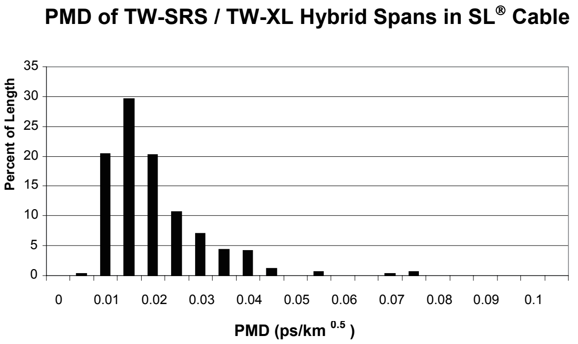

Fig.5. PMD of approximately 16000km TW-XL and TW-SRS hybrid spans in the SL® cable. The RMS average cable PMD is 0.031 ps/km$^{0.5}$. The average LMC PMD of the TW-XL and TW-SRS fiber is 0.031 ps/km$^{0.5}$ and 0.024 ps/km$^{0.5}$, respectively.

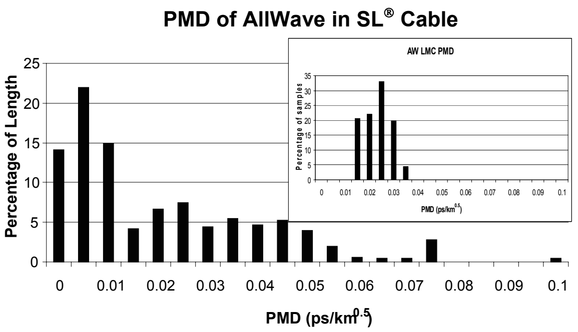

Fig.6. PMD of 7800 km of AllWave compensation fibers in the SL® cable. The RMS average cable PMD is 0.030 ps/km$^{0.5}$. The insert shows the LMC PMD distribution of the AllWave fibers. The average LMC PMD is 0.021 ps/km$^{0.5}$.

the fibers in the cables. It should be noted that for each fiber type, a small incongruence exists in the sets of fibers plotted in the fiber and cable PMD histograms, which is related to practical cable shop operational variations. However, the effects of these variations on the distributions and statistics are small.

The LMC values are typically slightly higher than the cable PMD. This is likely due the bending induced birefringence from the 320 mm diameter coil of the fibers during the LMC testing. So even with a coil diameter that is more than twice the recommended minimum coil diameter, bending induced DGD is seen.

Link design values for the above cable values (N= 20, Q = 10^{-4}) are 0.027 ps/km$^{0.5}$, 0.026 ps/km$^{0.5}$ and 0.021 ps/km$^{0.5}$ for TW-SRS, TW- XL and AllWave respectively. These values are quite similar to LDV for today's high quality terrestrial G652D fibers and NZDF fibers, specifying LDV values less than 0.04 ps/km$^{0.5}$ [15].

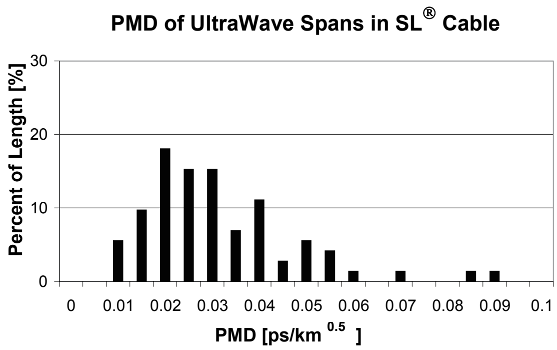

Fig.7. PMD of approximately 5000 km of UltraWave fibers in SL® cable. Average cabled PMD is 0.031 ps/km$^{0.5}$ The average DGD for the LMC samples of SLA and IDF are 0.019 ps/km and 0.045 ps/km, respectively. Combining the associated LMC PMD values yields an average fiber PMD of 0.034 ps/km$^{0.5}$.

For slope matched fiber spans only the cable data for the spliced sets, comprised of the two different fiber types are available.

Previous experience has indicated that LMC values of the two fiber types in the span will give a good estimate of the actual average PMD in cable. The SLA fiber with its large core and low core index is a very robust fiber with respect to PMD. As mentioned above, the IDF fiber needs the most attention if low PMD is required, even if it is only approximately one third of the span length. In Figure 7 the cable PMD of the slope matched fiber pairs is shown.

The level of PMD has improved since the first application of UltraWave fibers[16]. The primary improvement factor resulted from significant progress in producing IDF fibers with low PMD.

More recently, IDF fibers with LMC PMD levels around 0.03 ps/km$^{0.5}$ or lower have been produced, enabling span PMD levels of 0.02 ps/km$^{0.5}$. Keys to this improvement have been introducing reliable LMC measurements, optimizing LMC sampling, using the LMC measurements as feedback in identifying and continuously improving process parameters that influence PMD, optimizing fiber spinning, and finally, verifying the correlation between LMC values and actual cable performance.

4. CONCLUSION

In this paper we have shown that by employing stringent process control, and with advanced processing, it is possible to achieve PMD levels of 0.02 ps/km$^{0.5}$, both on submarine NZDF fiber spans and for slope matched fiber spans. This level of system PMD is needed for achieving 40 Gbit/s transmission over trans-oceanic distances.

5. ACKNOWLEDGEMENT

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