EVALUATION OF BIREFRINGENCE AND MODE COUPLING LENGTH EFFECTS ON POLARIZATION MODE DISPERSION IN OPTICAL FIBERS

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Abstract- **Polarization mode dispersion (PMD) is of real concern in long-haul high-bit rate systems. The optical bandwidth of coherent communication systems with common polarization control can be severely limited by PMD. The present work is aimed at examining effects of birefringence and mode coupling length on PMD. Therefore, analyses have been performed on spooled and cabled single-mode optical fibers. Measurements show that average polarization mode coupling length of cabled fibers is 62 times greater than that of spooled fibers. This accounts for the larger PMDs of cabled fibers. Moreover, observing the shift of PMD spectrum over a wide wavelength interval as a function of temperature, internal stress combined with an elliptical deformation of the core is shown to be the dominant source of birefringence in the type of cable examined.**

I. INTRODUCTION

Polarization mode dispersion (PMD) is an important bandwidth-limiting phenomenon for high bit rate communication systems. Also, transmission lengths for 10 Gbps systems with optical amplifiers can be limited to 150 km because of the high PMD values of some optical fibers that are currently in use. Since the seminal work of Poole and Wagner, many papers were published that expanded the theoretical and experimental foundations of PMD in optical fibers [1-7]. Although, the theory is very useful in determining the impacts of PMD on optical communications systems, it does not help in determining the exact cause of the PMD of a specific optical fiber, i.e. the birefringence can be of any type and also the birefringence and polarization mode-coupling length are interchangeable when the magnitude of the PMD is concerned.

This study is aimed at experimentally examining the causes of PMD in single-mode optical fibers. To discriminate between the two possible causes, i.e. birefringence and mode coupling length, an experiment is performed to determine the PMD and polarization mode coupling length of a fiber simultaneously by relating measurements on the entire cable with measurements on a short sample of the fiber. Measurements on both spooled and cabled fibers help in understanding whether the enhanced PMD is due to an increase in birefringence or mode coupling length. Results of a second experiment indicate that birefringence analysis of a whole optical fiber is possible, in case the internal stress makes the dominant contribution to the birefringence.

In the following section, the necessary theoretical background is given. In Section III, experimental methods are described and measurements are presented. Finally, in Section IV, measurement results are evaluated.

II. THEORETICAL BACKGROUND

The main sources of birefringence in standard telecommunication fibers are twist, noncircularity of the core, internal stress and bending. We will focus on the last two and others will not be discussed further. The birefringence due to internal stress, which also depends on the noncircularity of the fiber core, can be expressed as

$$\beta_{sc} = \frac{1}{2} k_0 n^3 \left(p_{11} - p_{12}\right)\left(1 - \frac{u^2}{V^2}\right)\frac{1+\nu_p}{1-\nu_p}\Delta\alpha\, \Delta T \frac{a-b}{a+b} \quad (1)$$

where k_0 is the free space propagation constant, n is the average refractive index of the fiber, p_{11} and p_{12} are the components of the strain-optical tensor of the fiber material, ν_p is the Poisson's ratio, $\Delta\alpha$ is the difference in thermal expansion coefficient between the core and cladding materials, ΔT is the difference between the glass softening temperature and temperature of the environment, a and b are the major and minor axes of the fiber core and V and u are the usual normalized parameters that can be computed with $V = k_0 b\left(n_1^2 - n_2^2\right)^{1/2}$ and $u = k_0 b\left(n_1^2 - n_b^2\right)$, respectively where n_b is the effective mode index along the minor diameter and n_1 and n_2 are the refractive indexes of the core and cladding regions, respectively. $(1- u^2/V^2)$ is

Table 1. Material constants of SiO_2

N	p_{11}-p_{12}	ν_p	α (SiO_2)	α ($0.25GeO_2$, $0.75SiO_2$)
1.46	-0.15	0.17	0.5 x 10^{-6} °C^{-1}	7 x 10^{-6} °C^{-1}

strongly frequency dependent but, if operation is restricted to near the higher mode cutoff in moderately elliptical cores, it has a value of order 0.5 [8]. Numerical values for material constants of (1) are given in Table 1.

Another type of birefringence results from bending and can be expressed as

$$\beta_{sc} = \frac{1}{2} k_0 n^3 (p_{11} - p_{12})(1 + \nu_p) \frac{r^2}{R^2} \qquad (2)$$

where r is the radius of the fiber cladding and R is the radius of bending [8].

The magnitude of the PMD can be accessed experimentally by measuring the differential group delay (DGD) τ of the polarization modes since PMD $<\tau>$ of a fiber is the average value of the DGD over a broad frequency range expressed in ps.$km^{-1/2}$.

PMD of an arbitrary fiber can be related to its birefringence and polarization mode coupling length properties as

$$< \tau > = \frac{h}{\sqrt{2}} \left(\frac{\partial \beta}{\partial \omega} \right) \left(\frac{2L}{h} - 1 + \exp\left[\frac{-2L}{h} \right] \right)^{1/2} \qquad (3)$$

where β is the average total birefringence, ω is the angular frequency, h is the polarization mode coupling length and L is the fiber length. This expression can be obtained from various fiber models, e.g. [4-6], the simplest of which is a concatenation of fibers whose lengths and birefringences are the same although birefringence axes have random orientations.

For short fibers, i.e. L<<h, PMD grows linearly with length and (3) can be rewritten as

$$< \tau > = \left(\frac{\partial \beta}{\partial \omega} \right) L \qquad (4)$$

For long fibers, i.e. L>>h, PMD grows with the square root of length and one can write

$$< \tau > = \left(\frac{\partial \beta}{\partial \omega} \right) \sqrt{hL} \qquad (5)$$

Considering (4) and (5), mode coupling length h can be obtained by measuring PMD of an entire fiber and a short sample of that fiber where fiber lengths are chosen properly so that (4) and (5) are satisfied.

Assuming that the average birefringence does not depend on the fiber length and replacing the derivative $\partial\beta/\partial\omega$ with β/ω since the most important contributions to the birefringence given in (1) and (2) are linearly proportional to ω, h can be expressed as

$$h = \left(\frac{< \tau_L > \omega_L}{< \tau_S > \omega_S} \right)^2 \frac{L_S^2}{L_L} \qquad (6)$$

where indices L and S denote long and short.

To obtain an average mode coupling length $<h>$ from measurements on several fibers, it is better to average the mode coupling rates $1/h$ rather than h itself by concerning fiber lengths as weighing factors. Then, $<h>$ can be computed with

$$< h > = \left(\sum_i l_i \right) \Bigg/ \left(\sum_i \frac{l_i}{h_i} \right) \qquad (7)$$

where l_i and h_i are the length and the mode coupling length of the i th fiber, respectively.

III. MEASUREMENT METHODS AND EXPERIMENTAL RESULTS

Some PMD measurements were performed with a polarization analyzer that uses Jones matrix method in a wavelength range of 1470-1560 nm while the rest ones were carried out with an optical spectrum analyzer in the range of 1200-1700 nm.

In the Jones matrix method [9,10], output state of polarization (SOP) is measured as a function of the wavelength with the help of predetermined input SOPs and the DGD is computed with

$$\Delta\tau(\omega) = 2\sqrt{\left| a'(\omega) \right|^2 + \left| b'(\omega) \right|^2} \qquad (8)$$

where a and b are the components of the Jones matrix for the fiber and their derivatives are approximated by $a'(\omega) \approx [a(\omega)-a(\omega+\Delta\omega)]/\Delta\omega$ etc. This method has the advantage of obtaining the DGD as a function of wavelength and the average PMD is comparable to PMDs obtained with other methods.

In optical spectrum analyzer setup, polarized broadband light is launched into the test fiber and the transmitted spectrum on the output is measured with the optical spectrum analyzer. The transmission spectrum typically exhibits a number of peaks and valleys. PMD can be computed from the number of these extrema N_e depending on whether the test fiber is regarded as long or short compared to the mode coupling length L_C. This method is also called the fixed analyzer method. Required

Table 2. Measured DGDs of long (*L*) and short (*S*) fibers, PMDs and computed mode-coupling lengths *h*

Fiber	τ_L (ps)	L_L (m)	PMD ($ps.km^{-1/2}$)	τ_S (ps)	L_S (m)	h (m)
1	0.46	750	0.53	0.011	10	409
2	0.07	750	0.08	0.001	10	641
3	0.52	750	0.60	0.006	10	989
4	0.29	750	0.34	0.013	10	132
5	0.15	750	0.17	0.004	10	121
6	0.44	750	0.51	0.007	10	540
7	0.58	2350	0.38	0.182	20	2.2
8	0.16	1685	0.12	0.031	20	5.3
9	0.07	1760	0.05	0.004	20	200
10	0.13	3270	0.07	0.012	20	7.5
11	0.30	4520	0.14	0.058	20	3.3

equations for PMD computations can be given as

$$< \Delta\tau >= \begin{cases} \dfrac{\pi N_e}{\Delta\omega}, & L < L_C \\ 0.824\pi \dfrac{N_e}{\Delta\omega}, & L >> L_C \end{cases} \qquad (9)$$

This method has the advantage of performing measurements on both long and short fibers with the same experimental setup by simply adjusting the wavelength range.

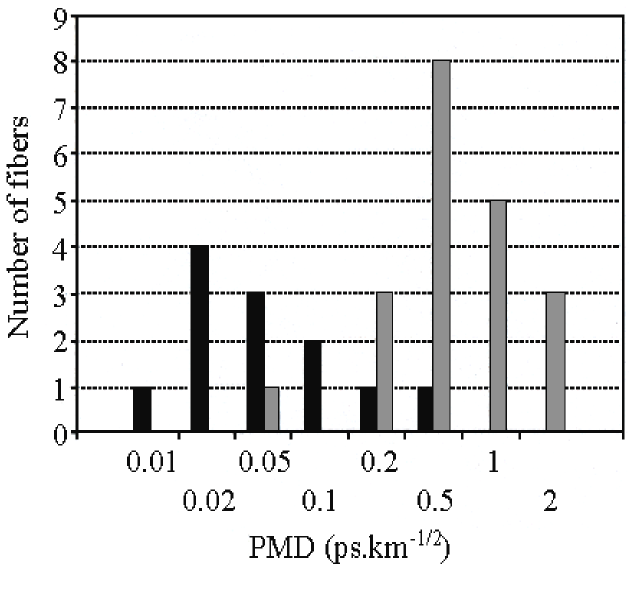

Fig. 1. Measured PMD values of spooled (black bars) and cabled (grey bars) fibers

The results of PMD measurements on both spooled and cabled fibers are shown in Fig. 1. Most of the measurements were performed with the polarization analyzer. All fibers were from the same manufacturer. Uncabled fibers were wound on transport spools and had lengths between 2 km and 13 km while cabled fibers had a typical length of 750 m. All cables were of the same design with six loose tubes and two copper wires helically wound around a central strength member. Each loose tube were containing a single fiber immersed in gel.

Six cabled and five spooled fibers were also measured over the entire length as well as over a short length of 10 or 20 m cut in the optical spectrum analyzer. Using (6), polarization mode-coupling lengths were computed from these measurements. Experimental and computational results are shown in Table 2. In some cases, the short sample may not be representative for the entire fiber. This is probably the reason for the high mode coupling length value of the spooled fiber 9.

It is not likely that birefringence due to the experimental setup significantly effects the computed *h* values. This would primarily effect the results on short fibers and imply that the real mode coupling length is even higher since h is inversely proportional to the PMD of short fiber.

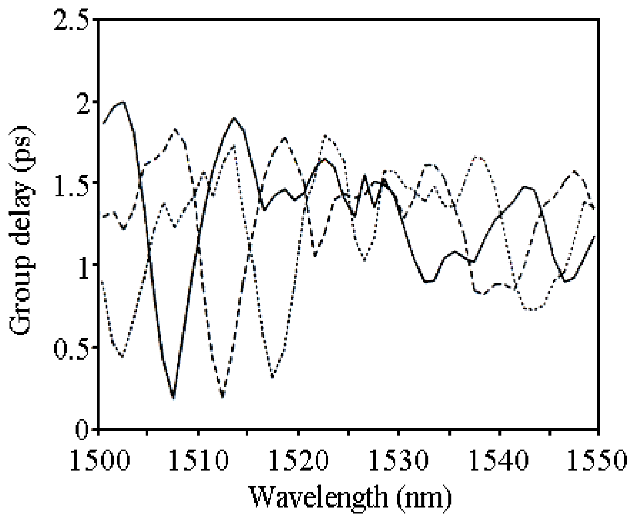

Fig. 2. PMD spectra of a cabled fiber at temperatures of 30°C (solid), 25°C (dashed) and 20°C (dotted)

Using the polarization analyzer, we measured DGD as a function of wavelength at three different temperatures for one of the cables. Results are shown in Fig. 2. The temperature was set homogeneously throughout the fiber by resistive heating since the cable had two internal copper wires. As shown in Fig. 2, the temperature change caused PMD spectrum to shift in wavelength rather than alter in shape. The average shift for measurements on two different fibers in the same cable was about –1.0 nm/°C as shown in Fig. 3.

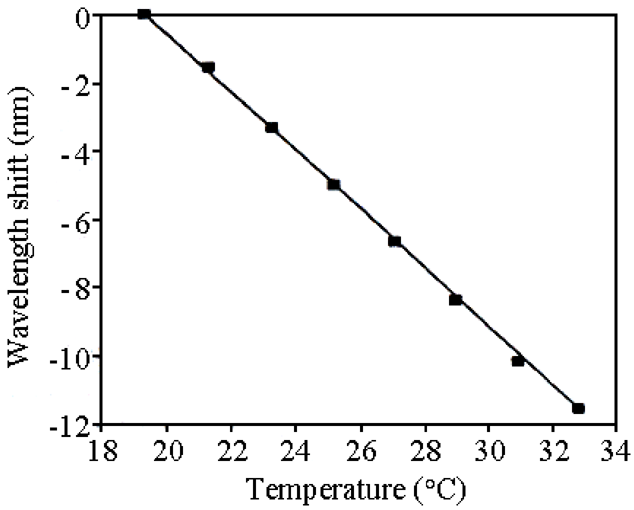

Fig. 3. Shift of the PMD spectrum of a cabled fiber

IV. EVALUATION OF EXPERIMENTAL RESULTS

It is obvious in Fig. 1 that PMDs of cabled fibers are significantly larger than that of spooled fibers. Comparing mode coupling lengths of cabled fibers with that of spooled fibers from Table 2, the larger PMDs of cabled fibers can be related to their much longer h values with respect to spooled fibers. Using (7), $<h>$ can be computed as 265 m for cabled fibers and 4.25 m for spooled fibers resulting in a factor of 62 difference.

Variations in PMD values may occur among different cable designs. In the helically wound loose-tube filled will gel, which we used in our measurements, there is no mechanical contact between the fiber and the wall of the loose tube. Therefore, it might be said that fibers in a stranded loose tube cable can have very long polarization mode coupling length. This could be different in other cable types, e.g. sinusoidally stranded loose-tube cable, since a mechanical force is exerted on the fiber. Therefore PMD and coupling length analyses on various cable designs would be an interesting research.

After interpreting experimental results about the mode coupling length and its effects on PMD, let's look in some more detail at birefiringence properties of our test cable. In Section III, it was shown that PMD spectrum of a cabled fiber shifted in wavelength rather than alter in shape upon changing the temperature. In the simplified model of a fiber consisting of sections with uniform birefringences and random connection orientations, there are three effects that cause the PMD spectrum to change with temperature. The first one is the increase in the length of each fiber section due to thermal expansion. This causes variations in both the group delay between the polarization modes and the SOP at the end of the section. But this effect is very small since a fiber length of 1 km expands by only a few centimeters when the temperature is increased by 10°C. Second, as shown in (1), the birefringence itself depends linearly on temperature via the internal stress in silica fibers. Third, thermal expansion of buffering and coating materials may change the random mode coupling especially in spooled fibers wound with some tension.

In order to maintain the phase change of the optical field along each fiber section, an increase in fiber length can be compensated by an increase in wavelength since the most important birefringence sources are inversely proportional to wavelength as shown in (1) and (2). Therefore, using thermal expansion coefficients given in Table 1, it can be computed that the expansion effect would result in a small positive shift rate of about 0.01 nm/°C in the PMD spectrum of our test fiber.

It is also possible to compensate the change in the internal stress birefringence by a change in wavelength. To estimate the shift rate, the value of ΔT, i.e. temperature difference between the softening temperature of the type of glass of the fiber and room temperature (see (1)), must be known. The ΔT value differs according to dopant types used in the fiber but in any case, it is lower than the value for pure silica, which is 1500 °C. Therefore, a large negative shift in wavelength of about 1.3 nm/°C near 1500 nm is required to compensate for the change in internal stress birefringence.

The third temperature effect –changes in the mode coupling due to thermal expansion of buffering and coating materials- cannot be compensated in a similar way due to its random nature.

Concerning the results of our experiments, the observed wavelength shift in the PMD spectrum can only be explained with internal stress in combination with elliptical core deformation being the dominant source of birefringence. If other sources of birefringence are sufficiently large to cause significant changes in the SOP, variations in the shape of the PMD spectrum will also be expected to occur as well as the wavelength shift. There is a good agreement between the observed shift rate of – 1.0 nm/°C and the estimated value of – 1.3 nm/°C considering the approximations in ΔT values. It is suggested in [8] that it is better to change the factor $\Delta\alpha\Delta T$ of (1) by an integral $\int\Delta\alpha\Delta T$ as thermal expansion coefficients increase substantially at high temperatures. Then, required wavelength shift to compensate for a temperature change would be smaller than for a linear dependence of the birefringence on temperature. This nicely explains the wavelength shifts found experimentally.

V. CONCLUSION

Experimental analyses have been performed on spooled and cabled single mode optical fibers to examine effects of birefringence and mode coupling length on polarization mode dispersion. Measurements show that PMDs of cabled fibers are significantly larger than that of spooled fiber. This can be related with large polarization mode coupling length difference between cabled and spooled fibers since the average mode coupling length of cabled fibers was found to be 62 times greater than that of spooled fibers.

The large mode coupling lengths can be attributed to type of cable used in our measurements where no mechanical force is exerted on the fiber.

Internal stress combined with an elliptical core deformation is shown to be the dominant source of birefringence in the type of cable examined. This can be concluded from the observed wavelength shift of the PMD spectrum due to variations in cable temperature. The experimental results were found to be in good agreement with theoretical estimations.

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