Bending Induced PMD in Spun Erbium Doped Fiber

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Abstract *We have measured the DGD induced by bending in both active and passive Erbium Doped Fibers. We demonstrate, both theoretically and experimentally, non-trivial behaviour of PMD in spun Erbium Doped Fiber (EDF) when coiled to small diameters.*

Introduction

With a growing number of systems running at 10 Gbit/s and large interest in 40 Gbit/s systems, there is increased focus on Polarization Mode Dispersion (PMD). Even though EDF amplifiers only consist of tens of meters of EDF, the PMD tolerance on the fiber is tight. But measuring the correct PMD in an EDF is not trivial [1]. Characterizing the intrinsic birefringence originating from geometric deformities in the fiber will not necessarily reveal the performance of the fiber in a coiled configuration, due to the interference between the externally induced birefringence from bending and the intrinsic birefringence, mitigated from spinning the fiber during draw [2], [3]. In this paper we demonstrate that coiling a fiber to diameters less than 10 cm can lead to significant bending induced PMD. Furthermore, we show that coiling high PMD spun fiber leads to highly unpredictable results.

Birefringence theory

The total birefringence in a fiber is the vector sum of the individual birefringences [4]. When the coil diameter is below 5 cm, the birefringence induced in low PMD fibers by bending is by far the dominating term. When bending a fiber, tension is applied to the outer portion of the fiber. This tension presses laterally on the inner portion, which is in compression. The birefringence induced from this second order transverse stress is [5]

$$\beta_b = 0.5kC_s(\omega)\left(\frac{d}{D}\right)^2$$

where *d* is the fiber cladding diameter, *D* is the bending diameter and C_s is a material parameter. The Differential Group Delay (DGD) is

$$DGD_b = \frac{\partial \beta_b}{\partial \omega} \approx \frac{\beta_b}{\omega} = \frac{0.137}{c}\left(\frac{d}{D}\right)^2$$

This result applies to weakly guiding silica fibers independent of core diameter and index profile.

Experimental setup

Whether measuring active or passive EDF the wavelength interval is important. We used the Jones Matrix Eigen analysis (JME) method to determine the DGD and measured both DGD and DOP from 1510 to 1640 nm. The DOP data were used to determine the usable wavelength interval for DGD. The PMD is the average of the DGD values vs. wavelength. We used 10 m of fiber in all measurements, which is comparable to the length in an EDFA and sufficiently low to avoid random mode coupling.

Three passive EDFs with standard cladding diameter of 125 µm were measured in 4 different bending configurations: Loose coil (D=25 cm) and wound on spools of diameters 11, 5 and 3 cm. Twists and tension were minimized during winding. Fiber No. 1 had a very low intrinsic PMD of 0.3 fs/m, No. 2 had a higher intrinsic PMD of 1.7 fs/m, and No. 3 was a test sample with a very high intrinsic PMD of 10 fs/m.

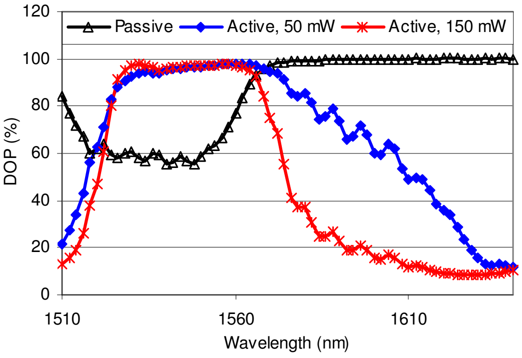

Fig. 1: DOP vs. WL for both passive and active EDF.

For the passive EDF the DOP is 60-90% between 1510 and 1570 nm. In this interval the laser is absorbed by the erbium ions and the signal reaching the polarization analyzer is a mix of polarized ASE from the signal laser and unpolarized ASE generated in the EDF by the signal laser. Only for wavelengths above 1580 nm, where the erbium absorption is low, the DOP~100% and the DGD can be determined.

For the active EDF the signal is not sufficiently amplified below 1530 and above 1565 nm, and unpolarized ASE dominates the analyzed light. Between 1530 and 1565 nm the laser signal is sufficiently amplified for the analyzer to determine the state of the polarization vector.

Experimental results

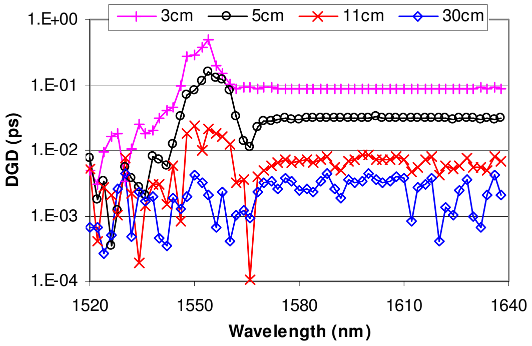

Fig. 2: DGD vs. wavelength for a passive fiber in different coils. For the loose coil configuration the DGD is very low and close to the resolution of the instrument. As the coil diameter decreases, the bending induces stress and the DGD increases and becomes deterministic and wavelength independent.

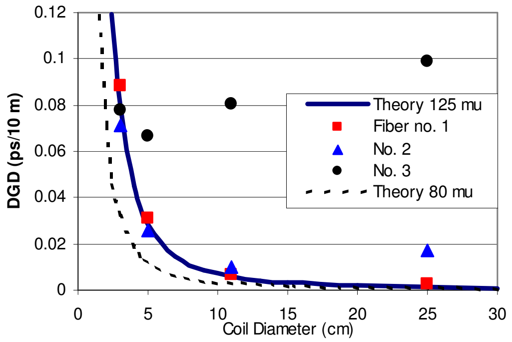

Fig. 3: DGD vs. bending diameter. Fiber No. 1 follows exactly the theoretical model for bending induced birefringence. Fibers 2 and 3 show more unexpected behaviour: The DGD decreases when the fiber is coiled. The dashed curve shows the (theoretical) bending induced DGD in an 80 μm fiber.

Theoretical wave-plate model

Simulations were performed using a wave-plate model to investigate the impact of systematic birefringence [6]. The general birefringence β_G in the model consists of an intrinsic birefringence β_I (mitigated from spinning the fiber during draw) and an externally induced birefringence β_b, in this case from bending the fiber. The model handles mechanical twist and mode coupling (the mode coupling length is here assumed to be longer than the fiber length).

$$\vec{\beta}_G = \begin{pmatrix} \beta_b + \beta_I \cos(2(\alpha(z)+\tau)) \\ \beta_I \sin(2(\alpha(z)+\tau)) \\ g(\tau) \end{pmatrix}$$

Knowing manufacturing details of the applied spin function *A(z)* (*$\alpha(z)$=A'(z)*) the mechanical twist τ and the intrinsic beat length of the fiber, we can simulate the total DGD as a function of the externally induced birefringence (in this case as coil diameter).
Simulations were performed on 10 m of fiber divided into 1000 wave-plates of width 0.01 m.

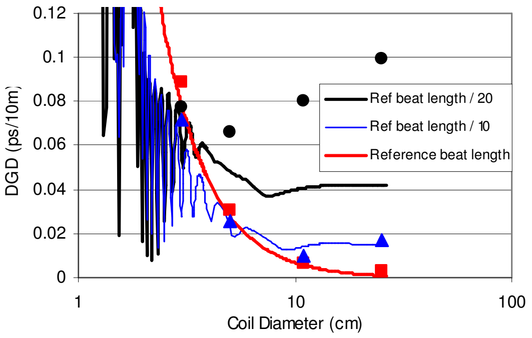

Fig. 4: Simulations of DGD vs. bending diameter for different values of intrinsic beat length along with data from fig. 3. When the beat length decreases, it interferes with the spin period resulting in a quickly varying PMD. Such extreme variations would be very difficult to resolve experimentally, but show that PMD is very difficult to predict when bending high PMD fibers.

Conclusion

We have demonstrated that measurement conditions are very important in characterizing PMD in Erbium Doped Fibers. Considerations have to be made about the fiber length, the wavelength interval, the signal laser and the degree of polarization.
Winding a spun EDF to small coil diameters leads to unpredictable PMD values if the intrinsic PMD of the fiber is not sufficiently low. Using EDFs with low intrinsic PMD (< 1 fs/m) are always preferential because birefringence induced from the bending will follow the theoretical curve. Spun fibers with higher intrinsic PMD (> 1 fs/m) can for certain coil diameters actually benefit from the bending, but the bending induced PMD will generally be very difficult to predict unless the spinning parameters (spin type, amplitude and period) are precisely known. In all low PMD fibers though, the bending induced birefringence dominates for coil diameters less than 5 cm and leads to significant increase in the PMD value. Using EDFs with smaller cladding diameter can reduce this bending PMD penalty.

References

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